Dense matter equation of state from heavy-ion collisions and neutron stars

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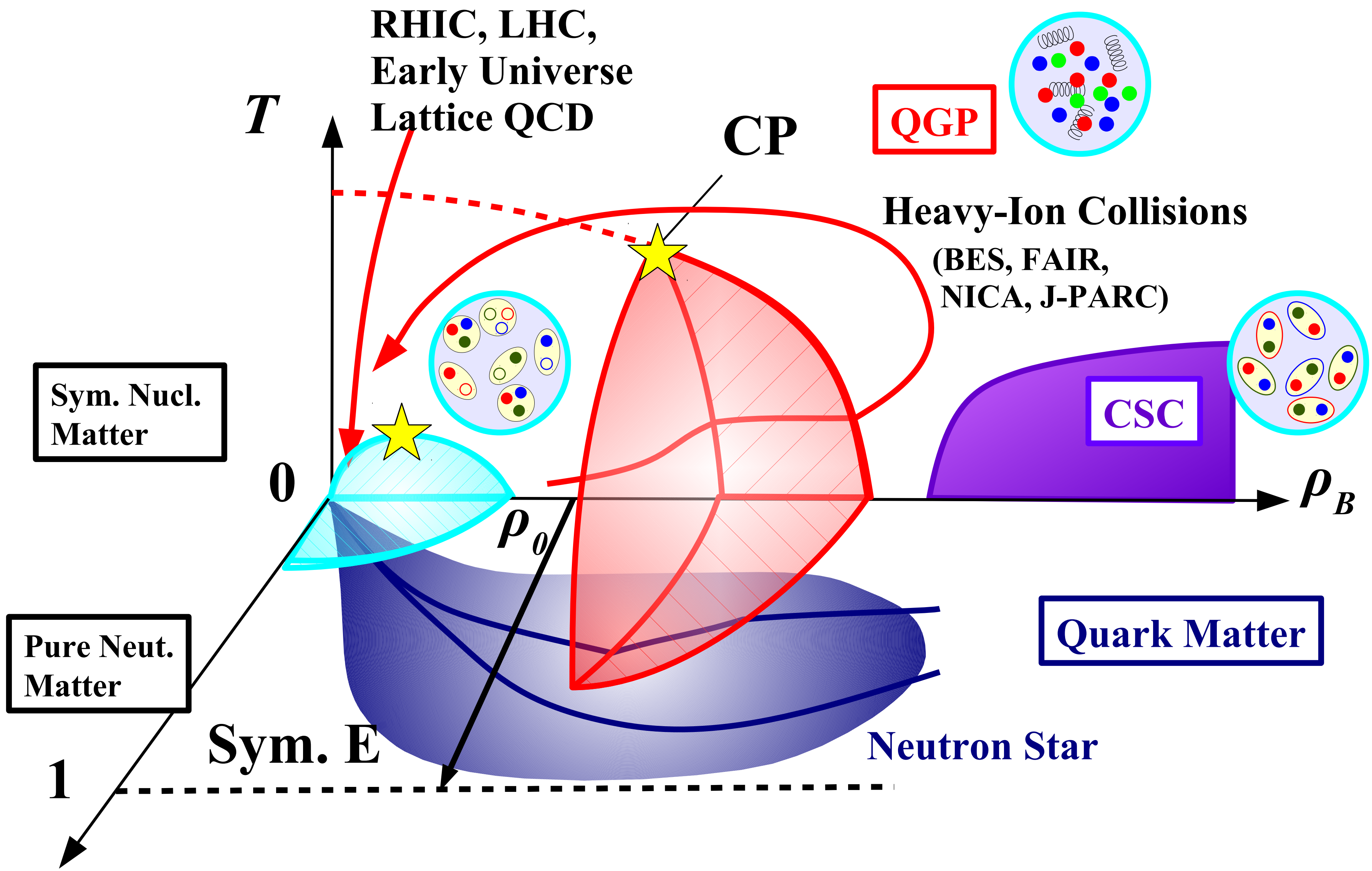
Strangeness and charm in hadrons and dense matter
May 15-26, 2017, YITP, Kyoto, Japan.

Y. Nara, H. Niemi, A. Ohnishi, H. Stoecker, PRC94 ('16), 034906.
AO, K. Tsubakihara, T. Harada, JPS Conf. Proc. 14 (2017), 020811
AO, K. Tsubakihara, T. Harada, work in prog.

QCD Phase Diagram



$\delta=(N-Z)/A$ (or $Y_Q(\text{hadron})=Q_h/B\sim(1-\delta)/2$)

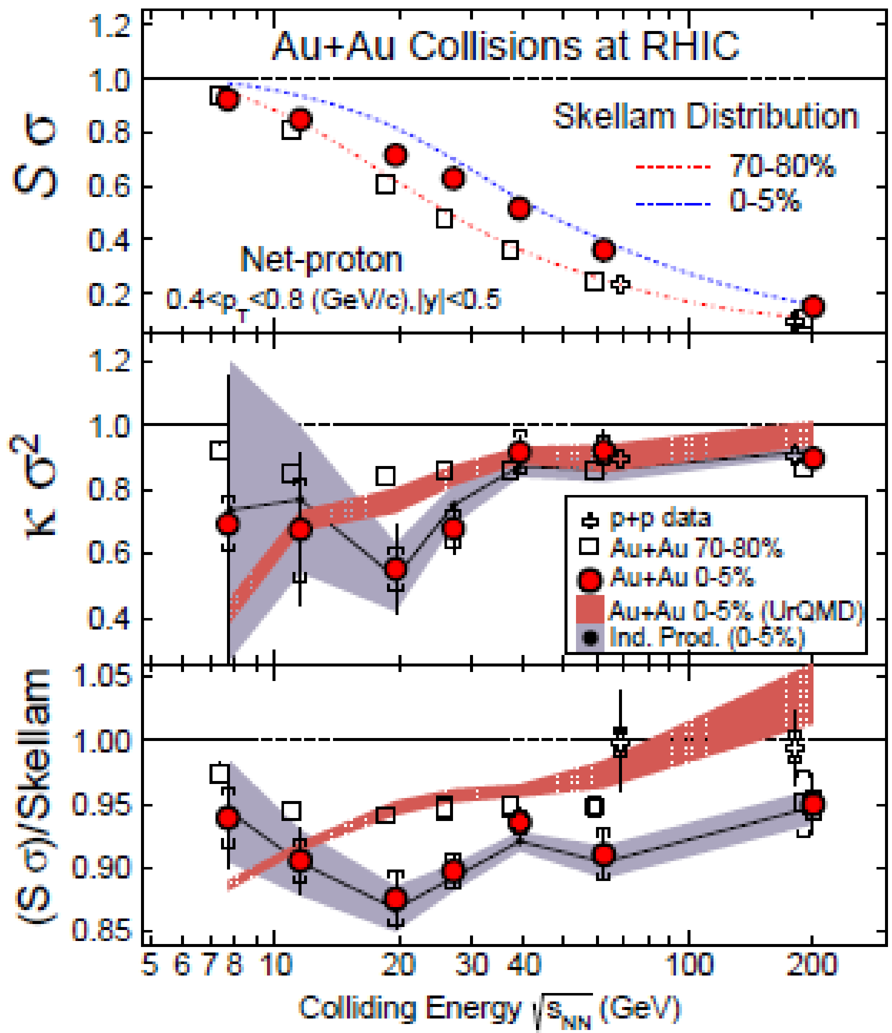
Dense matter EOS probed via heavy-ion collisions

Signals of QGP formation & QCD phase transition

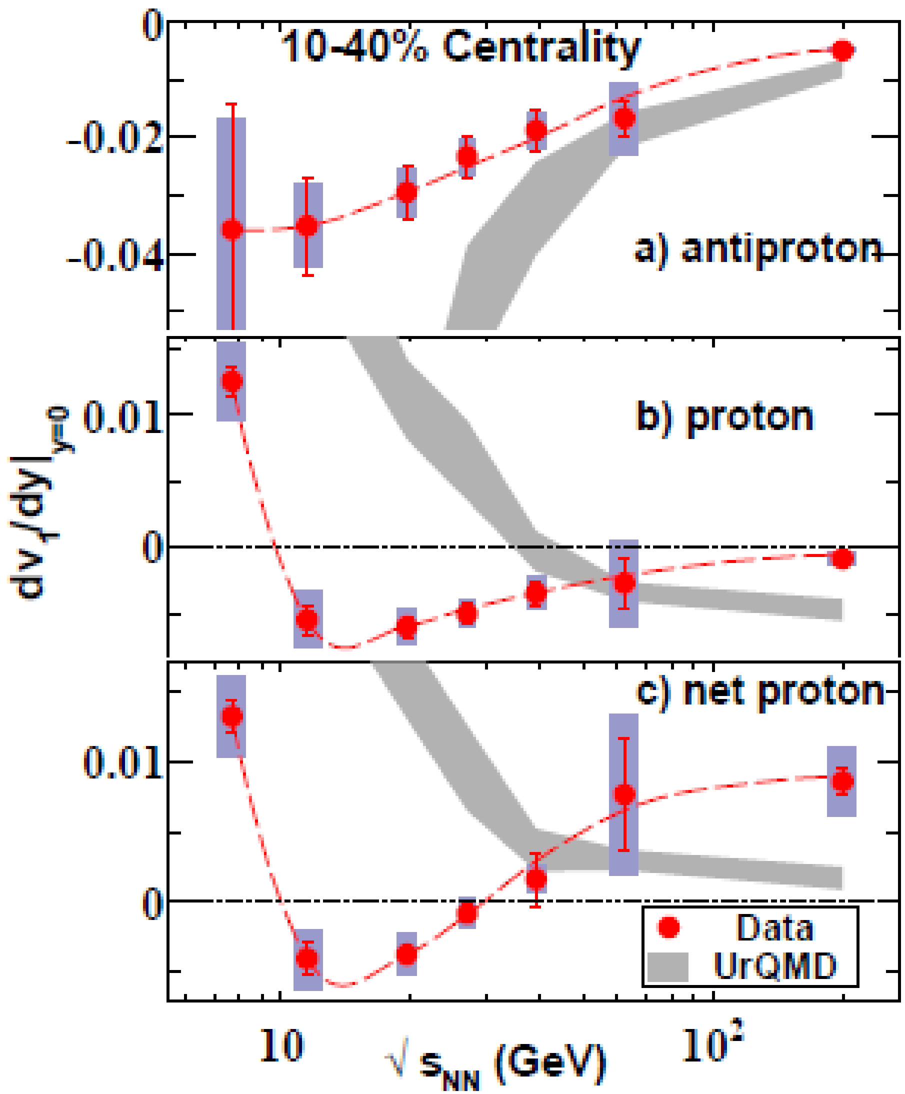
- Signals of QGP formation at top RHIC & LHC energies
  - Jet quenching in AA collisions (not in dA)
  - Large elliptic flow (success of hydrodynamics)
  - Quark number scaling (coalescence of quarks)
- Next challenges
  - Puzzles: Early thermalization, Photon v2, Small QGP, …
  - Study of hot matter under various extreme conditions
  - Discovery of QCD phase transition
- Signals of QCD phase transition at BES energies ?
  - Critical Point → Large fluctuation of conserved charges
  - First-order phase transition → Softening of EOS

→ Non-monotonic behavior of
proton number moment ($\kappa\sigma^2$) and collective flow (dv_1/dy)

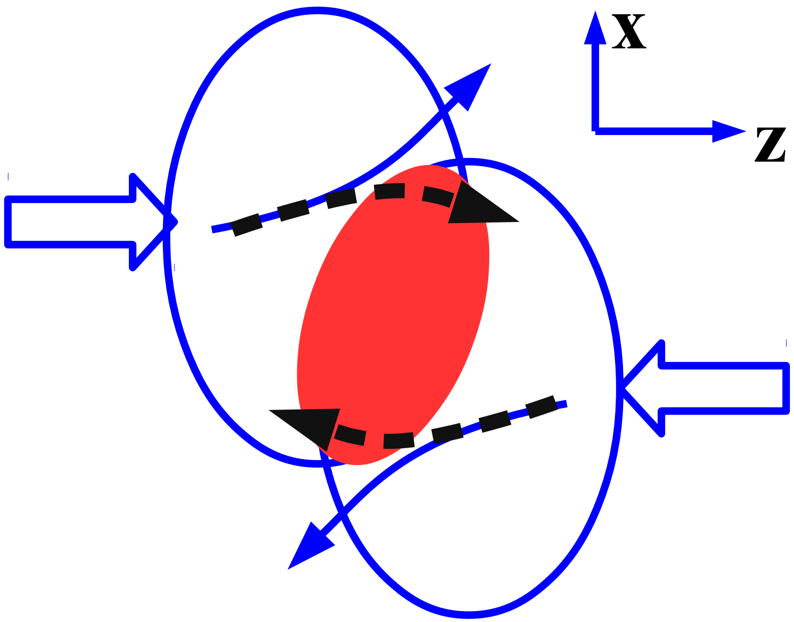
Net-Proton Number Cumulants & Directed Flow



STAR Collab. PRL 112('14)032302

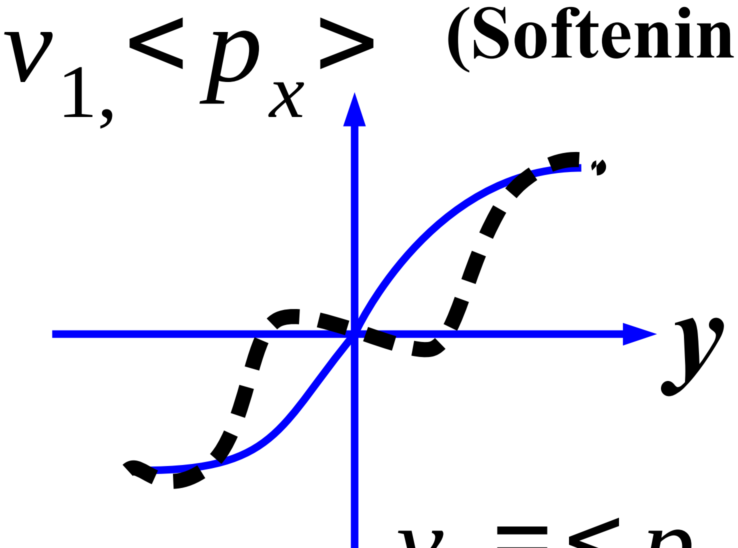


STAR Collab., PRL 112('14)162301.



- v_1 or $<p_x>$ as a function of y is called directed flow.
- Created in the overlapping stage of two nuclei
  → Sensitive to the EOS in the early stage.
- Becomes smaller at higher energies.

Attraction (Softening)

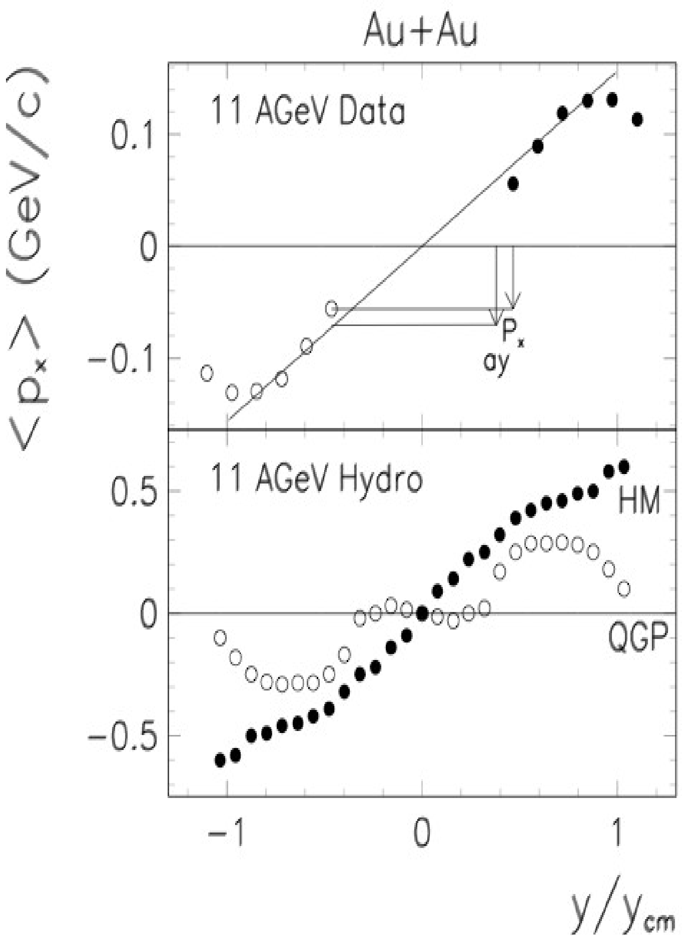


> ***How can we explain non-monotonic dependence of dv_1/dy ?***
> ***→ Softening or Geometry***

$$v_1 = < p_x / p > = < \cos \phi >$$

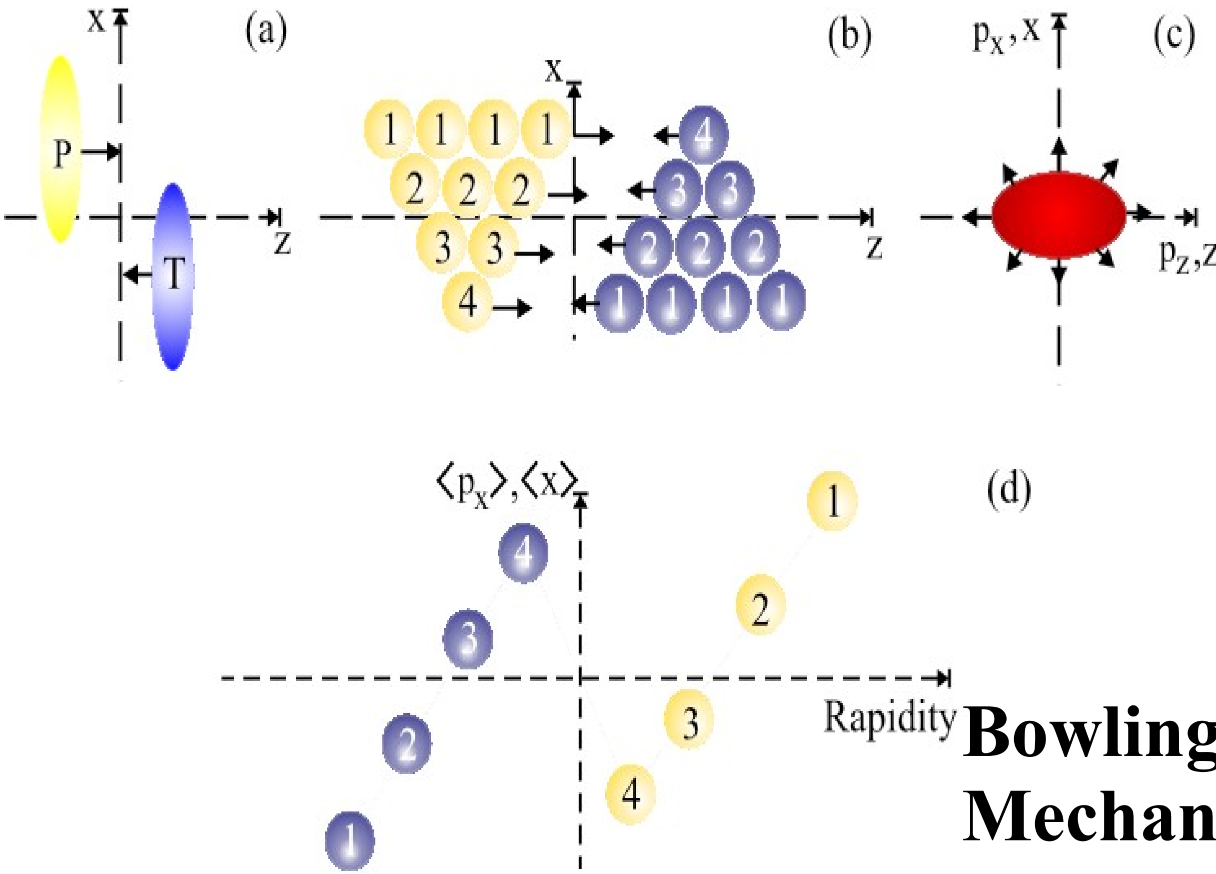
Does the "Wiggle" signal the QGP ?

- **Hydro predicts wiggle with QGP EOS.**



L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.

- **Baryon stopping + Positive space-momentum correlation leads wiggle (w/o QGP)**



Bowling Pin Mechanism

R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

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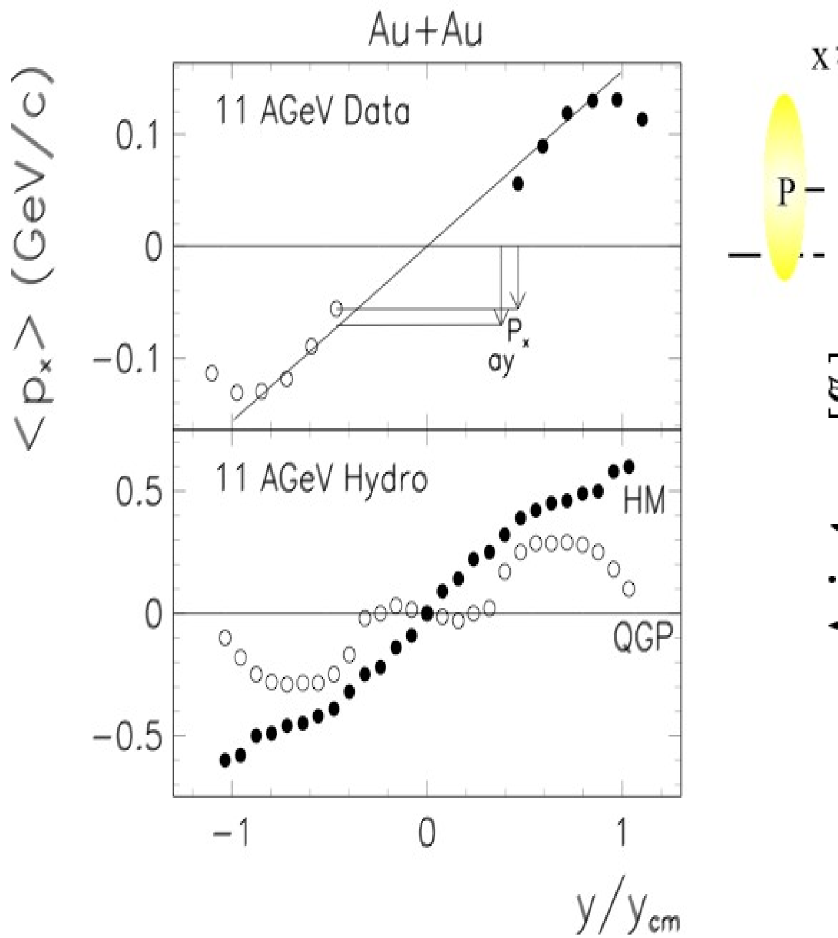

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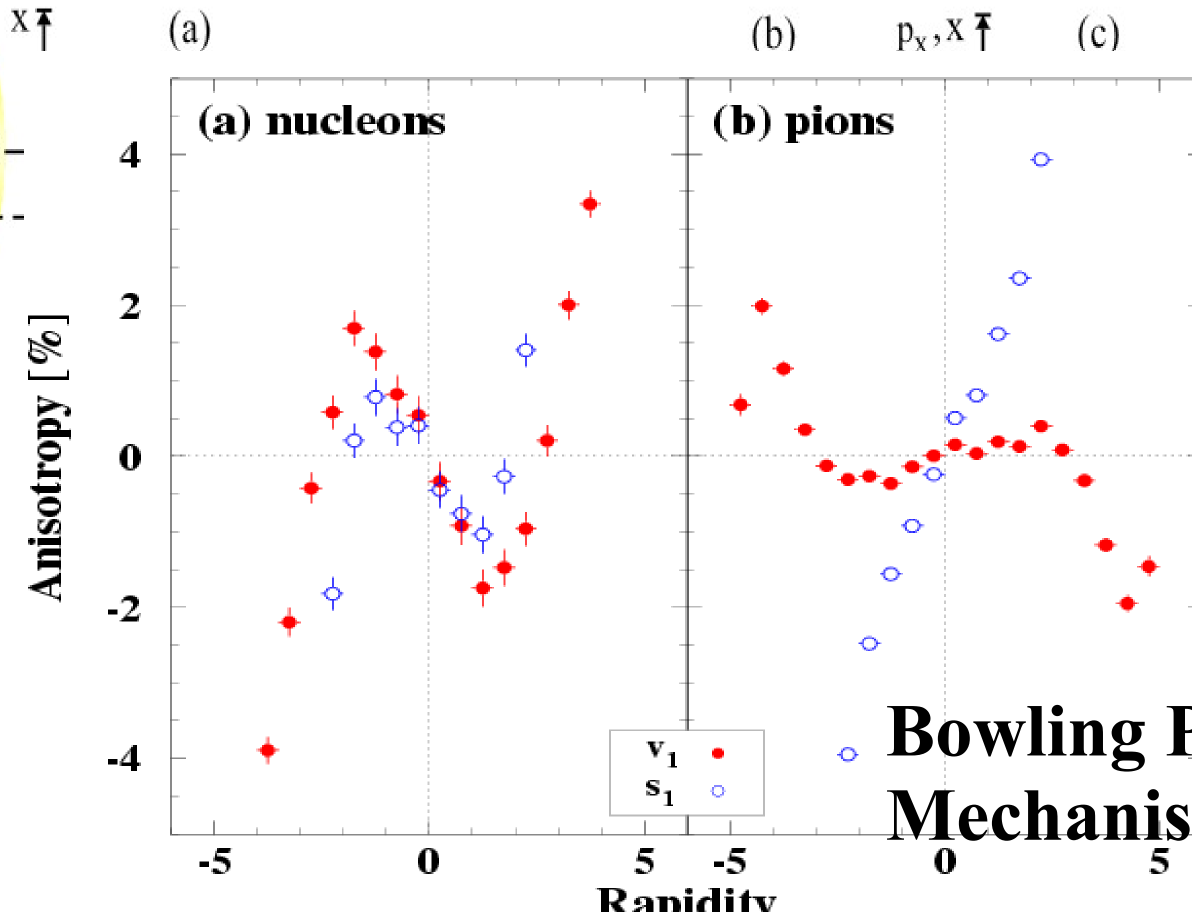


Bowling Pin Mechanism

R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

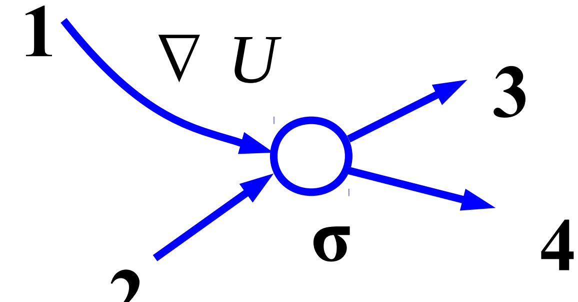
Does Directed Flow Collapse Signal Phase Tr. ?

- **Negative dv_1/dy at high-energy ($\sqrt{s_{NN}}$ > 20 GeV)**
  - **Geometric origin (bowling pin mechanism), not related to FOPT**
    R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL84,2803('00)
- **Negative dv_1/dy at $\sqrt{s_{NN}} \sim 10$ GeV**
  - **Yes, in three-fluid simulations. → Thermalization ?**
    Y. B. Ivanov and A. A. Soldatov, PRC91('15)024915
  - **No, in transport models incl. hybrid.**
    E.g. J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stoecker, PRC89('14)054913.
    Exception: *B.A.Li, C.M.Ko ('98) with FOPT EOS*

> ***We investigate the directed flow at BES energies in hadronic transport model with / without mean field effects with / without softening effects via attractive orbit.***

Transport Model

- **Boltzmann equation with (optional) potential effects**
  E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190



$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla U \cdot \nabla_p f = I_{\rm coll}$$

$$I_{\rm coll}(\mathbf{r},\mathbf{p}) = -\frac{1}{2}\int \frac{d\mathbf{p}_2}{(2\pi)^3} d\Omega\ v_{12}\,\frac{d\sigma}{d\Omega}\,[f f_2(1-f_3)(1-f_4)) - (12 \leftrightarrow 34)]$$

(NN elastic scattering case)

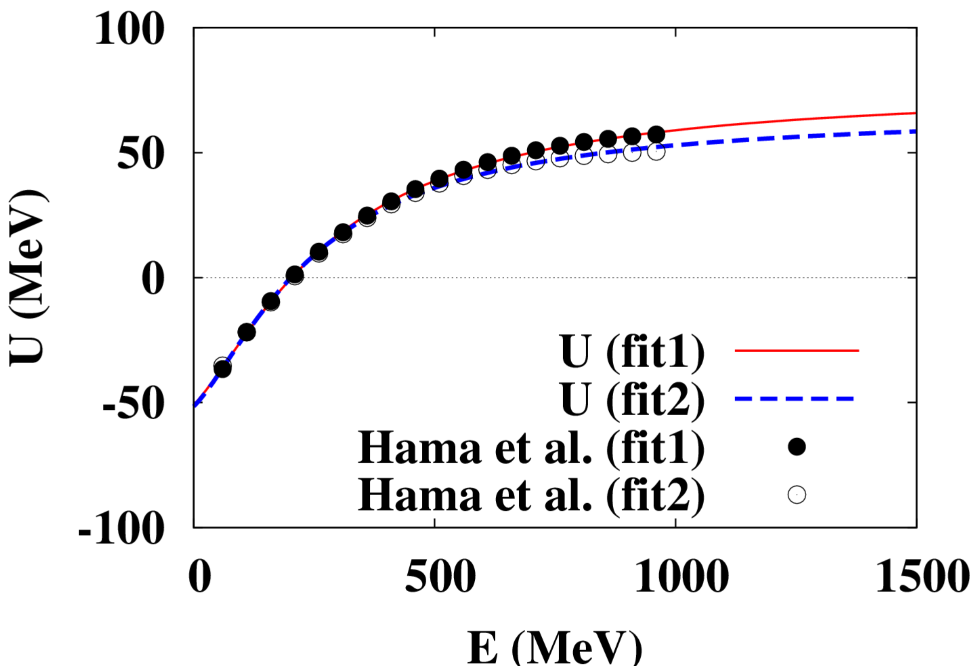
- **Hadron-string transport model JAM**
  - **Collision term → Hadronic cascade with resonance and string excitation**
    Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.
  - **Potential term → Mean field effects in the framework of RQMD/S**
    Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.
    Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.
    Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908.

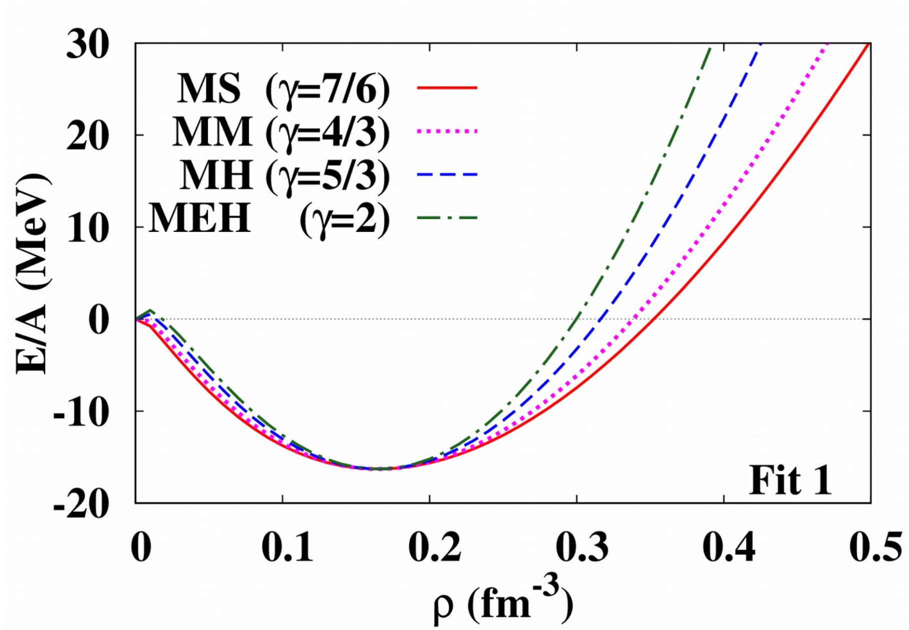
Mean Field Potential

- **Skyrme type density dependent + momentum dependent potential**

$$V=\sum_i V_i=\int d^3r\left[\frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{\beta}{\gamma+1}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}\right]+\sum_k\int d^3\boldsymbol{r}d^3\boldsymbol{p}d^3\boldsymbol{p}'\frac{C_{ex}^{(k)}}{2\rho_0}\frac{f(\boldsymbol{r},\boldsymbol{p})f(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\mu_k^2}$$

Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 (fm^{-1})	μ_2 (fm^{-1})	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6

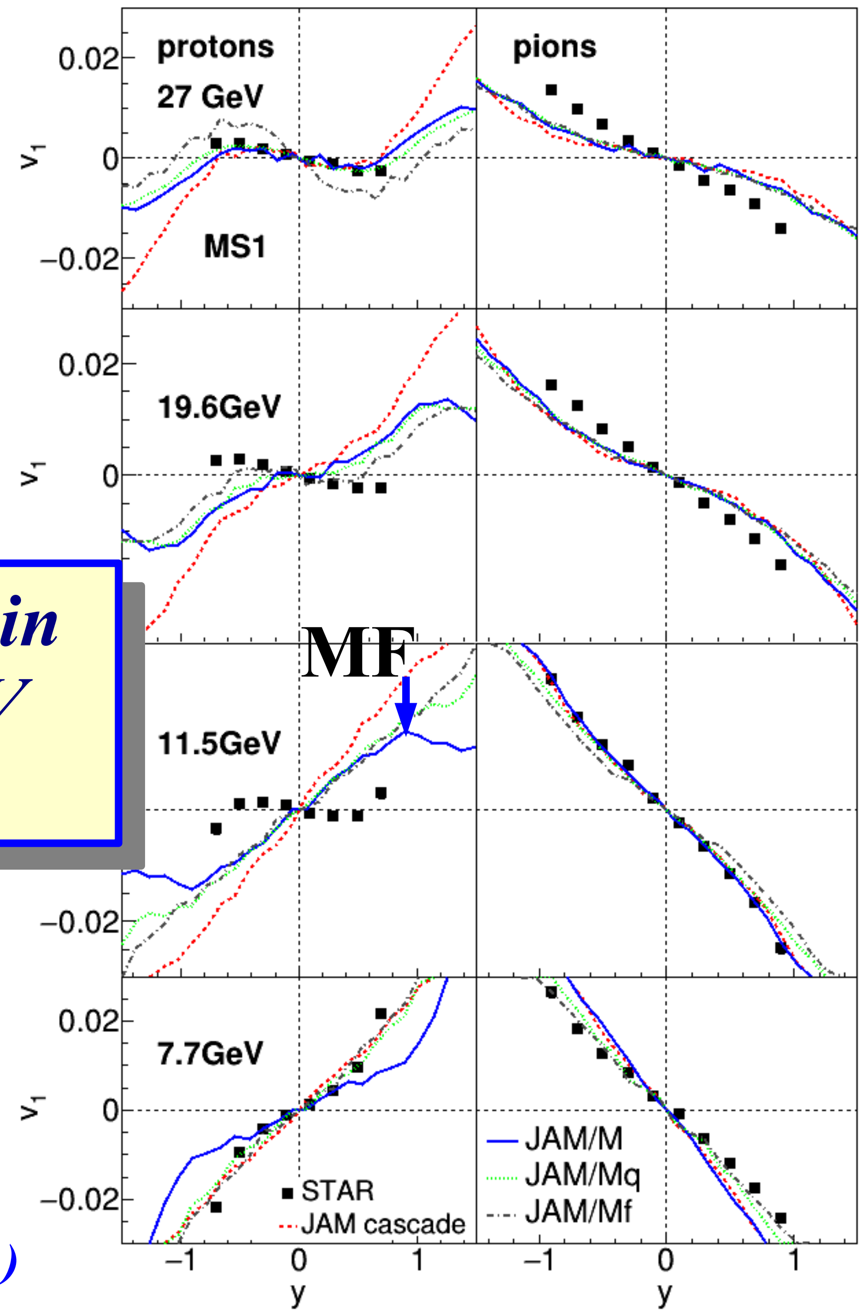




Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)
Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908.

Comparison with RHIC data on v_1

- Pot. Eff. on the v_1 is significant, but dv1/dy becomes negative only at $\sqrt{s_{NN}} > 20$ GeV.



Hadronic approach does not explain directed flow collapse at 10-20 GeV even with potential effects.

JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

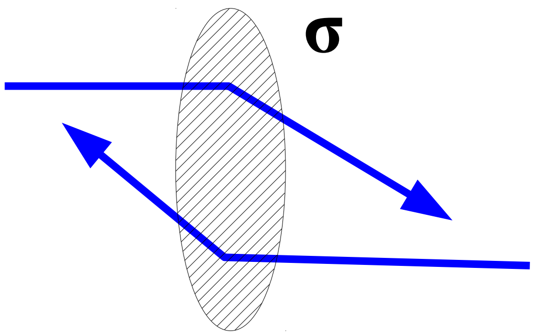
Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)

Softening Effects via Attractive Orbit Scattering

- **Attractive orbit scattering simulates softening of EOS**
  P. Danielewicz, S. Pratt, PRC 53, 249 (1996)
  H. Sorge, PRL 82, 2048 (1999).

$$P = P_f + \frac{1}{3TV} \sum_{(i,j)} (q_i \cdot r_i + q_j \cdot r_j)$$

(Virial theorem)



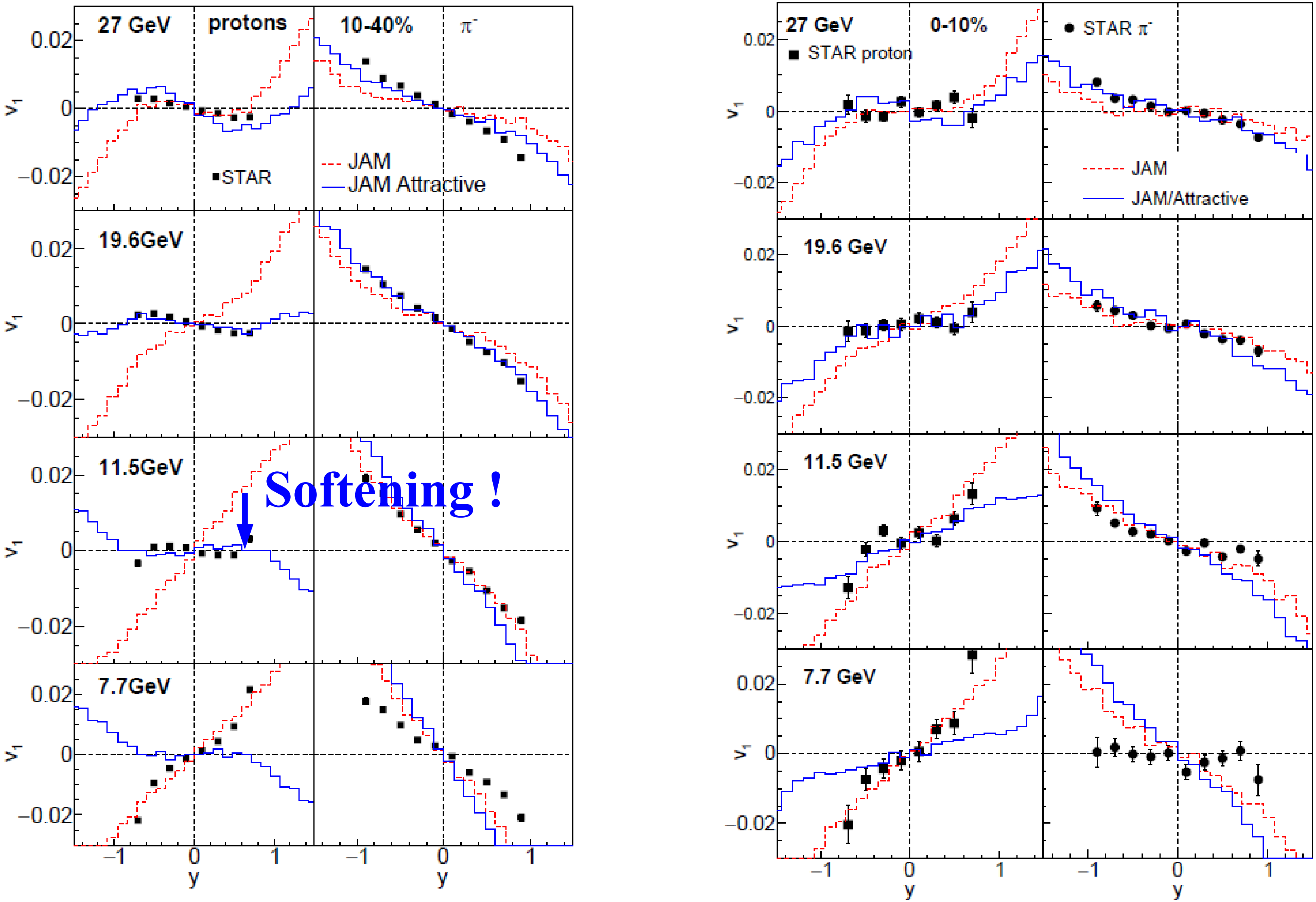
- **Attractive orbit → particle trajectory are bended in denser region**

> ***Let us examine the EOS softening effects,***
> ***which cannot be explained in hadronic mean field potential,***
> ***by using attractive orbit scatterings !***

Y. Nara, Niemi, AO, H. Stöcker ('16)

Directed Flow with Attractive Orbits

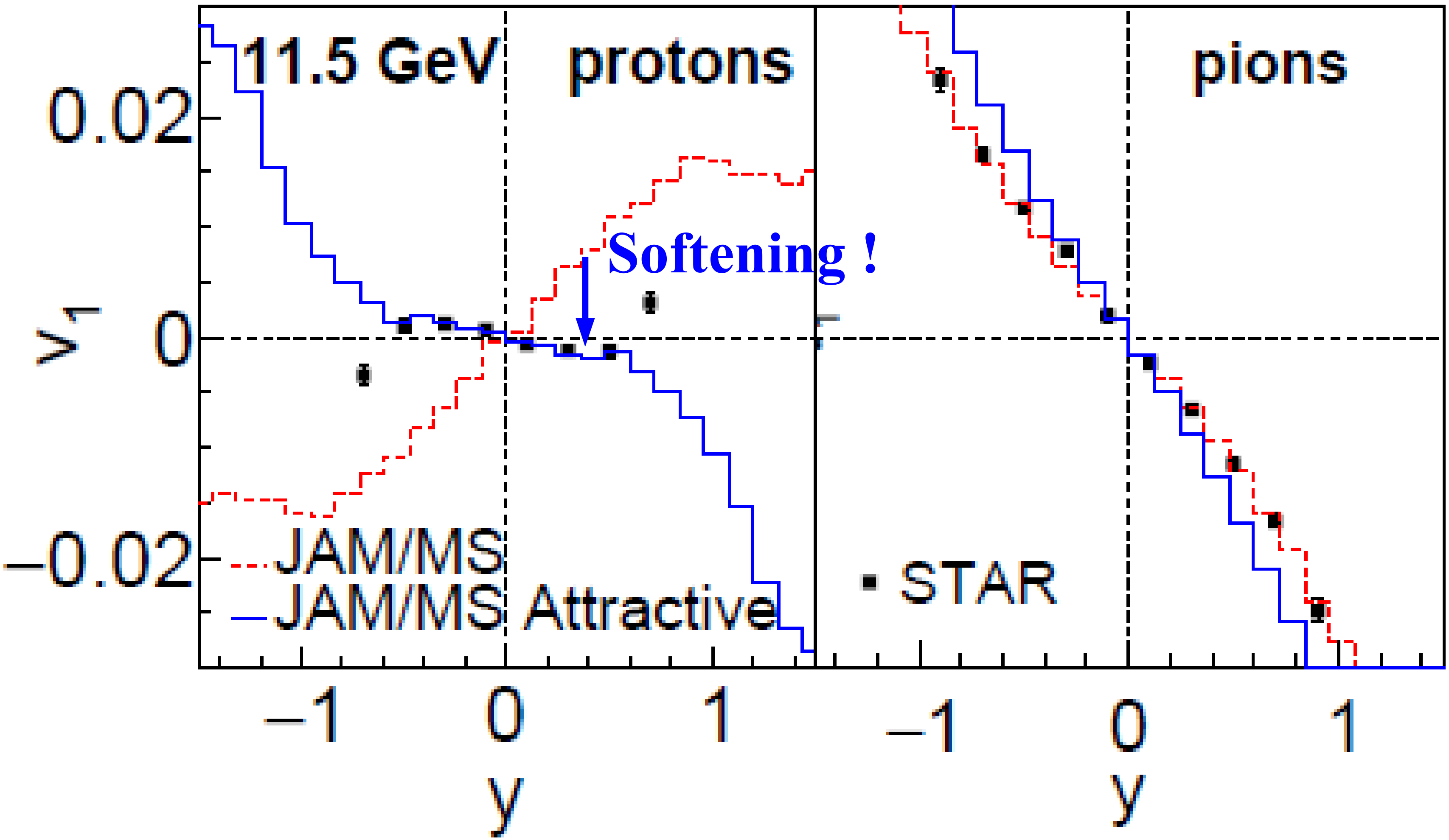
Nara, Niemi, AO, Stöcker ('16)



mid-central (10-40 %) **central (0-10 %)**

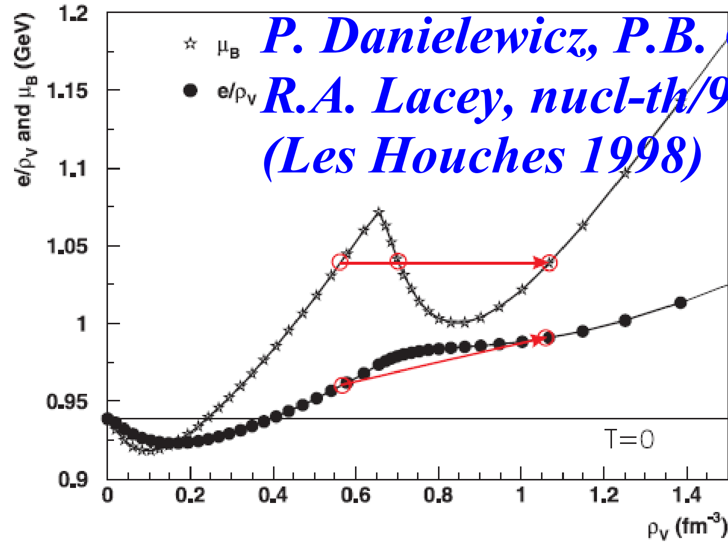
Mean Field + Attractive Orbit

Nara, Niemi, AO, Stöcker ('16)

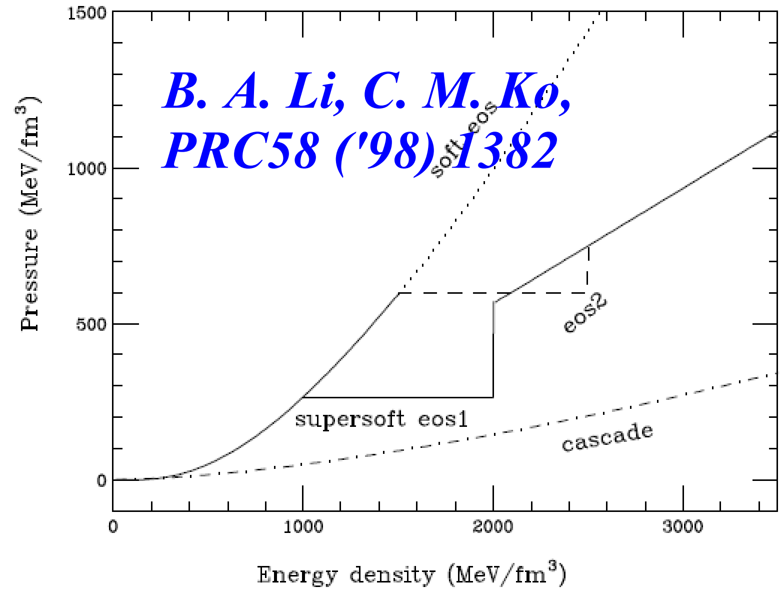


MF+Attractive Orbit make dv_1/dy negative at $\sqrt{s_{NN}}$ ~ 10 GeV

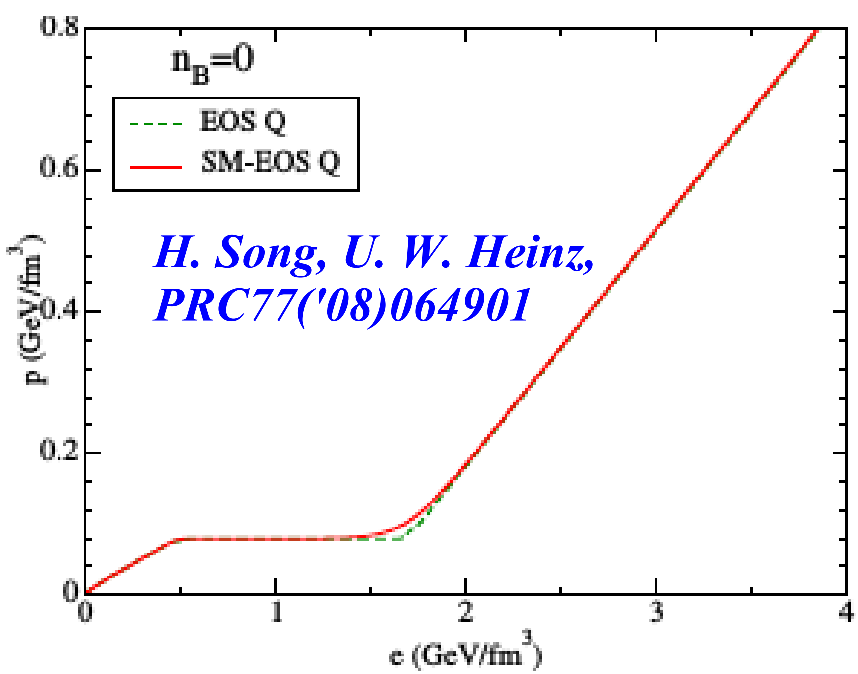
Softening: Where and How much ?



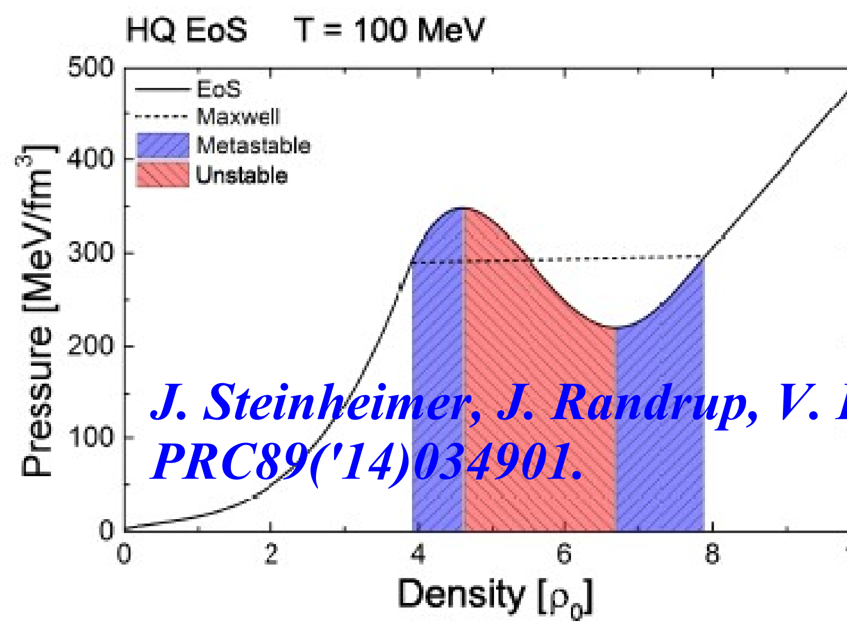
P. Danielewicz, P.B. Gossiaux, R.A. Lacey, nucl-th/9808013 (Les Houches 1998)



B. A. Li, C. M. Ko, PRC58 ('98) 1382



H. Song, U. W. Heinz, PRC77('08)064901



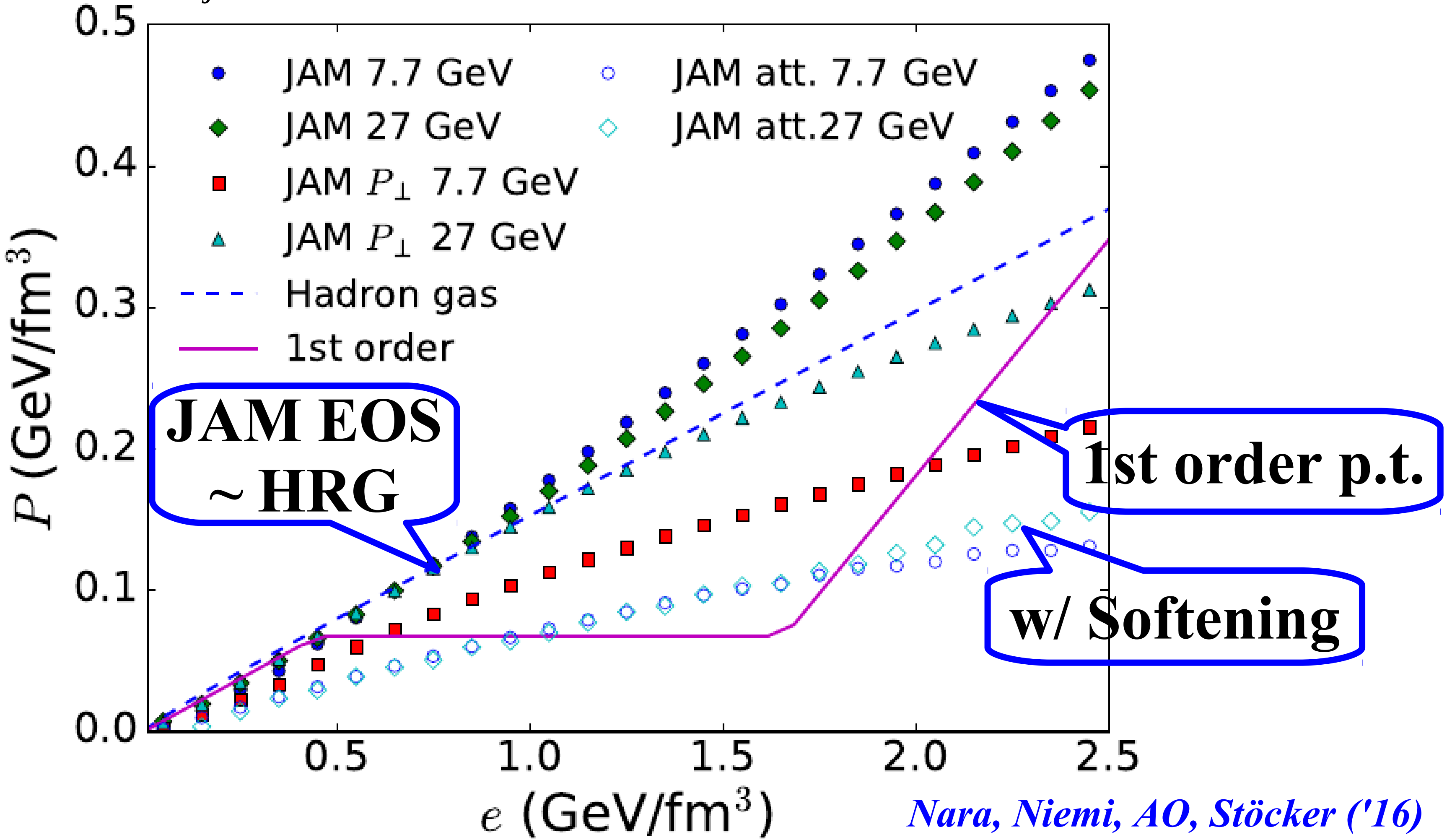
J. Steinheimer, J. Randrup, V. Koch, PRC89('14)034901.

Previous analyses: ρ_B=(3-10) ρ_0, P=(80-700) MeV/fm^3

Softening of EOS by Attractive Orbits

$$\Delta P = -\frac{\rho}{3(\delta\tau_i+\delta\tau_j)}(p_i' - p_i)^\mu (x_i - x_j)_\mu$$

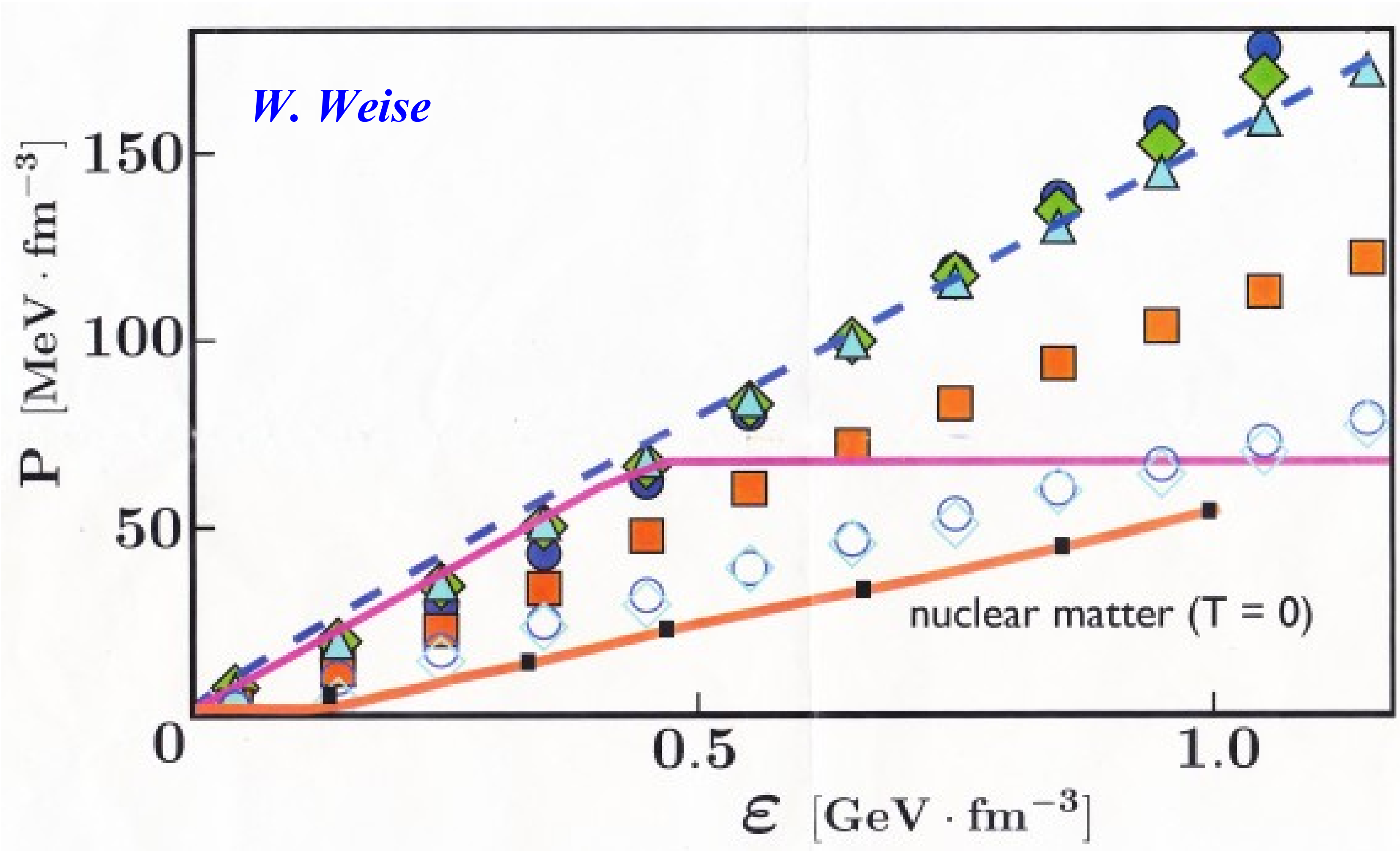
H. Sorge, PRL82('99)2048.



Nara, Niemi, AO, Stöcker ('16)

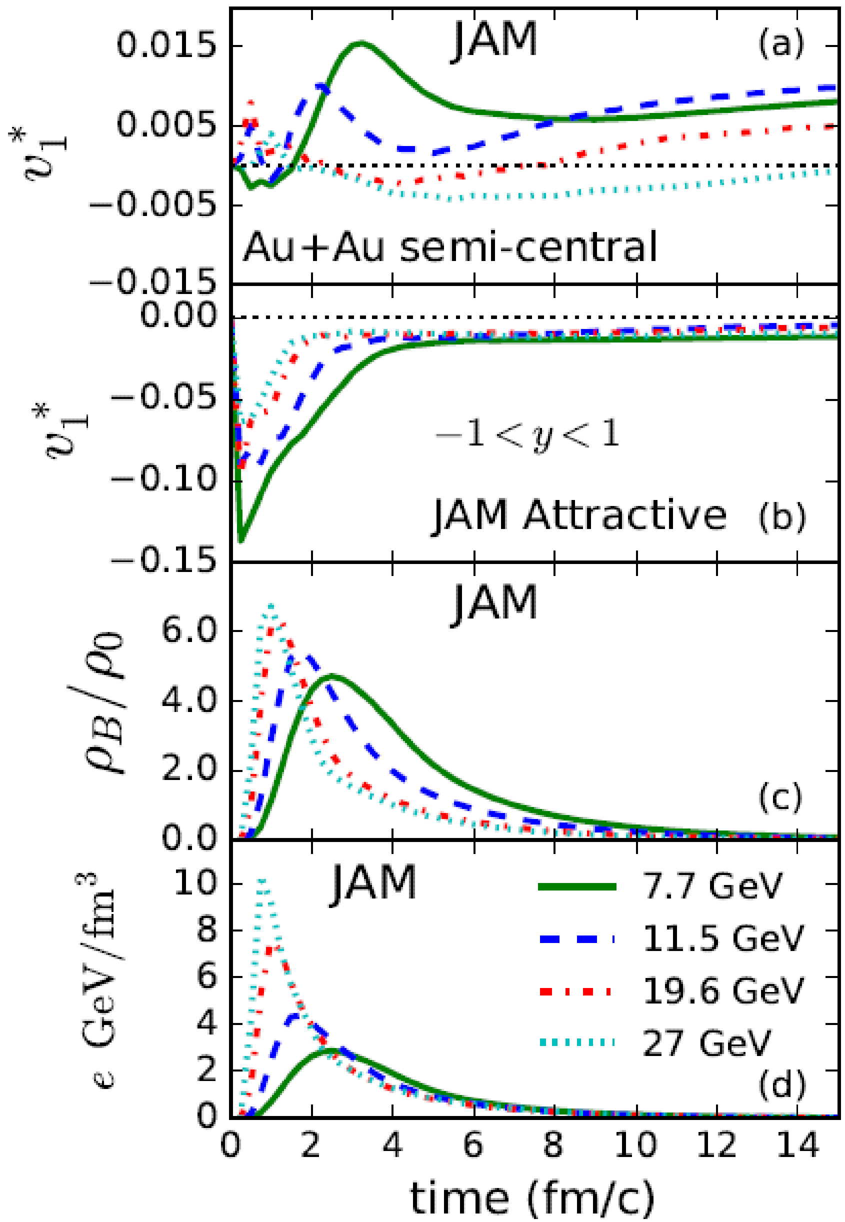
Pressure in simulated EOS ~ EOS-Q (e.g. Song, Heinz ('08))

Comparison with Cold Matter EOS



FRG EOS does not reach P~70 MeV/fm^3 at ε < 1 GeV/fm^3
→ Consistent with no FOPT at ε < 1 GeV/fm^3

At which density is the softening required ?



Softening is required at $\rho > 5\rho_0$

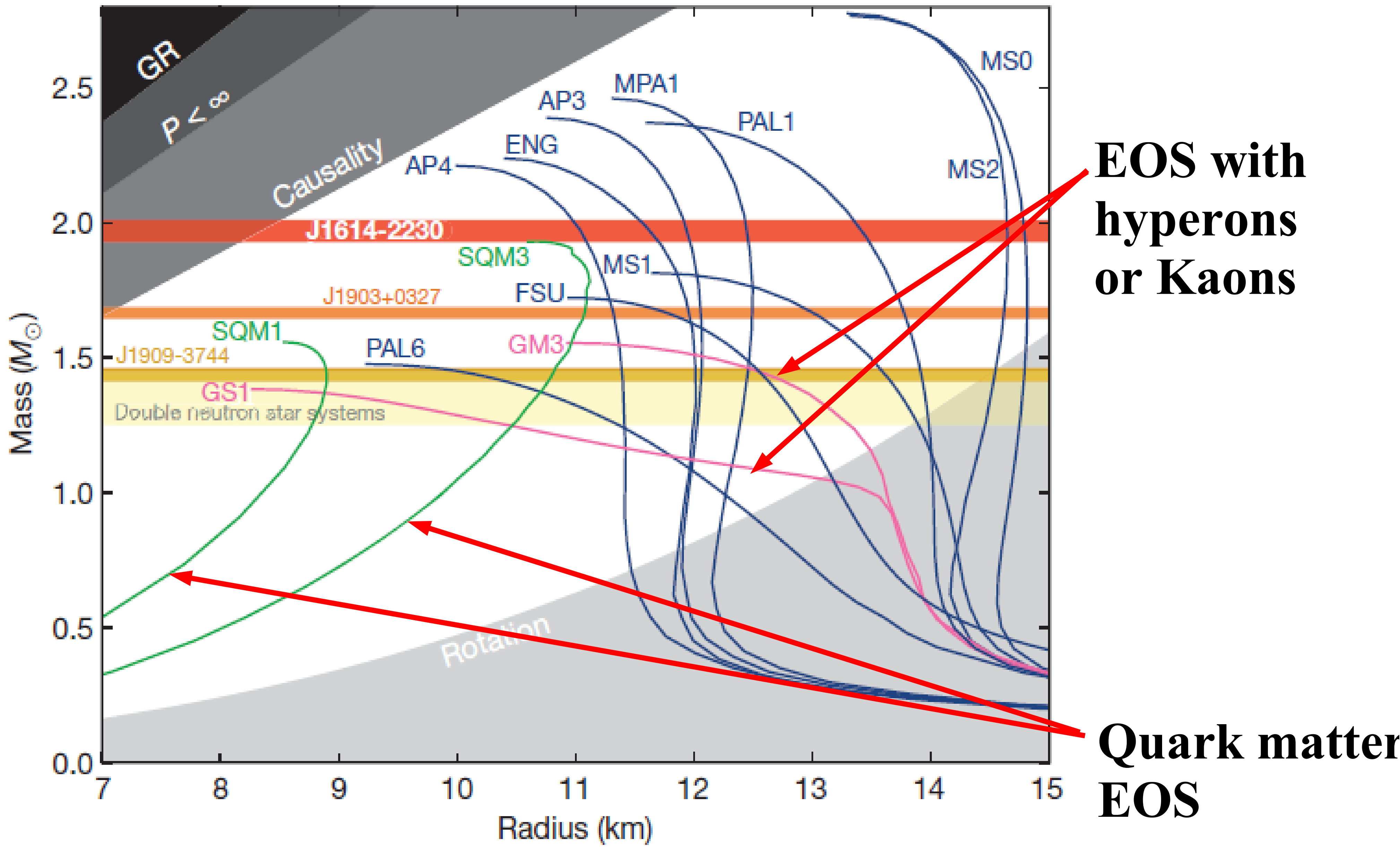
Short Summary of the 1st part

- **We may have seen QCD phase transition (1st or 2nd) signals at BES (or J-PARC) energies in baryon number cumulants and v_1 slope.**
- **Hadronic transport models cannot explain negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**
  - **Geometric mechanism becomes manifest at higher energies.**
- **Hadronic transport with EOS softening can describe negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**
  Y. Nara, H. Niemi, A. Ohnishi, H. Stoecker, PRC94 ('16), 034906.
  - **Attractive orbit scattering simulates EOS softening (virial theorem).**
  - **We need more studies to confirm its nature.**
    First-order phase transition ? Crossover ? Forward-backward rapidities ? MF leading to softer EOS ?
- ***We need "re-hardening" at higher energies, e.g. $\sqrt{s_{NN}} = 27$ GeV.***

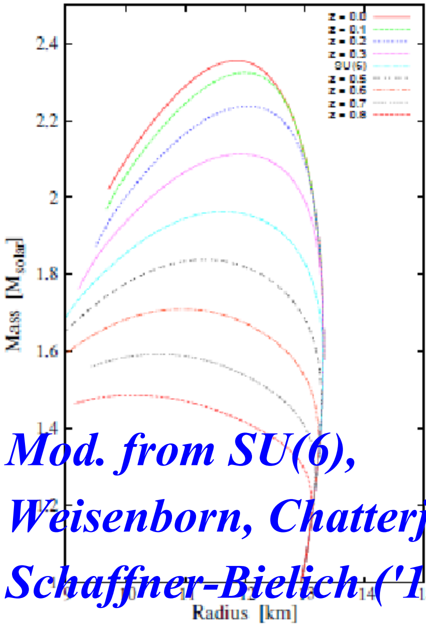
Dense matter EOS in neutron stars

Hyperon Puzzle

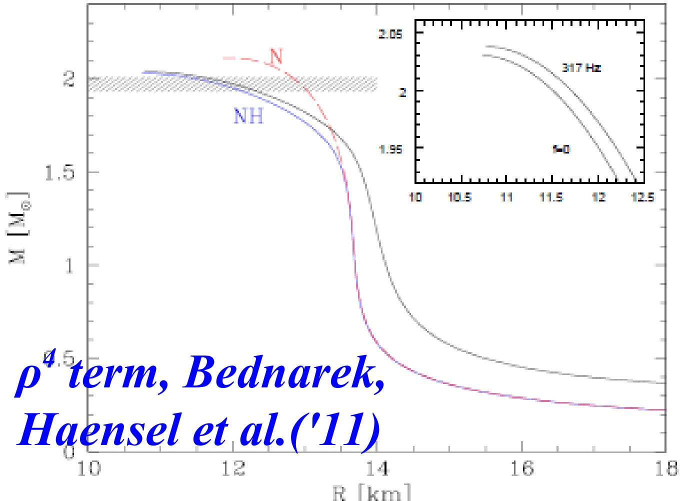
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



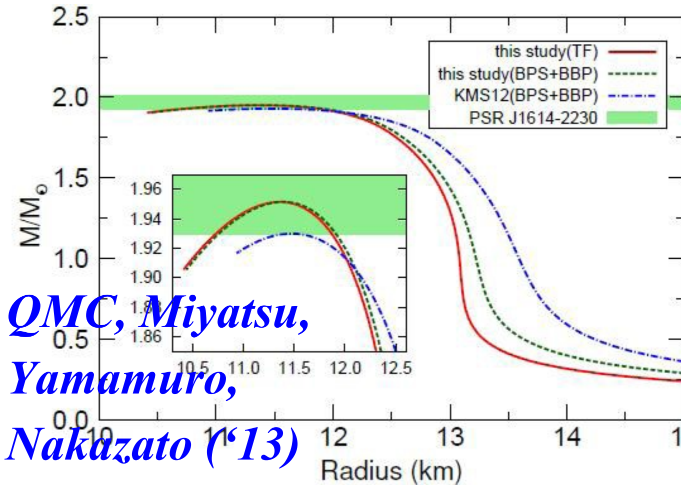
Massive Neutron Stars with Hyperons



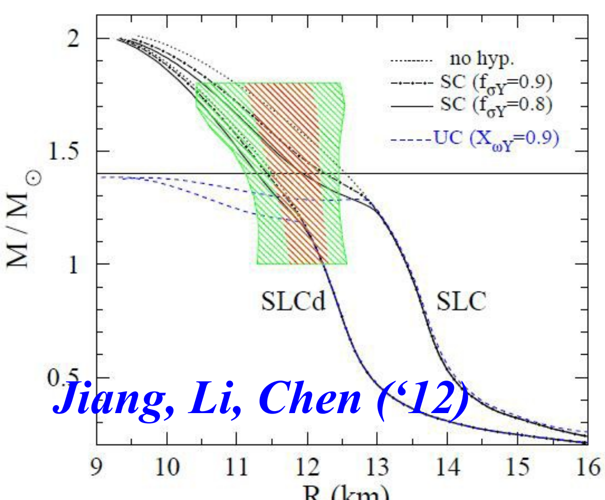
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



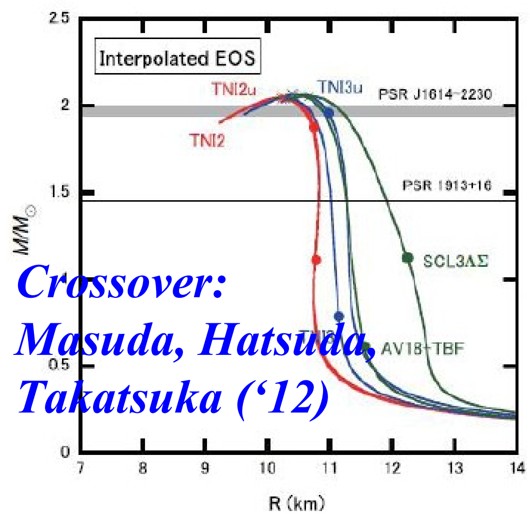
ρ^4 term, Bednarek, Haensel et al.('11)



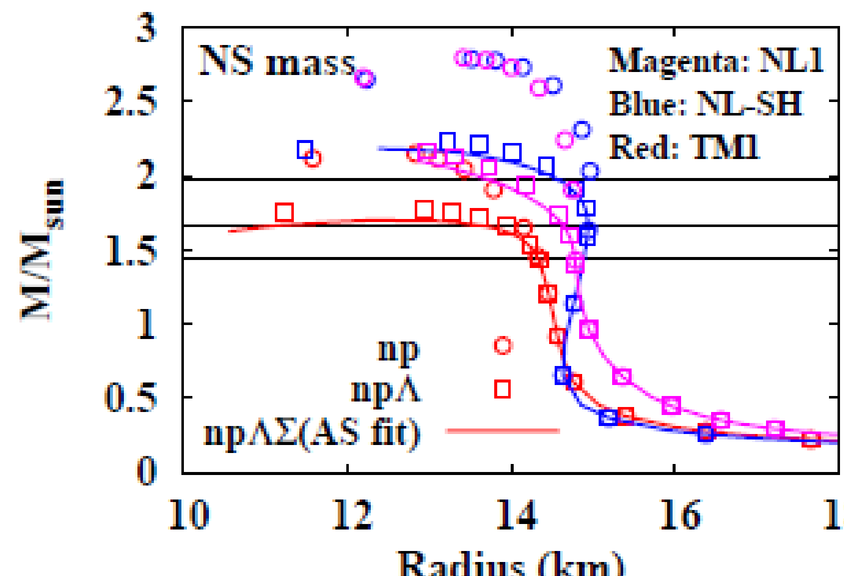
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)

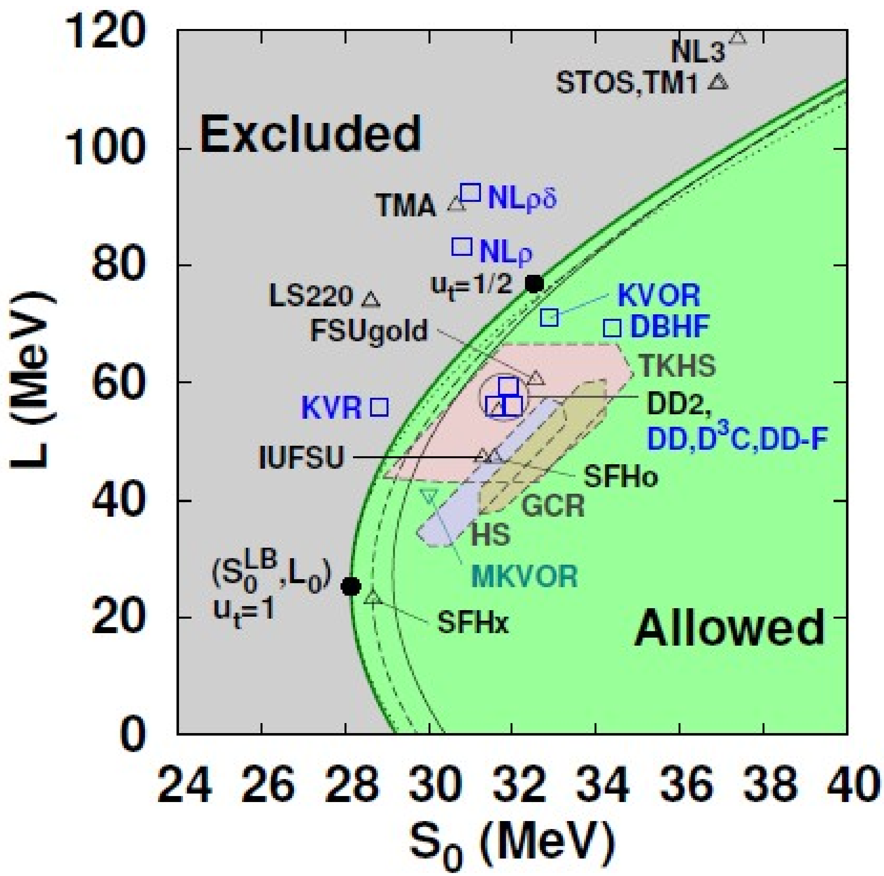


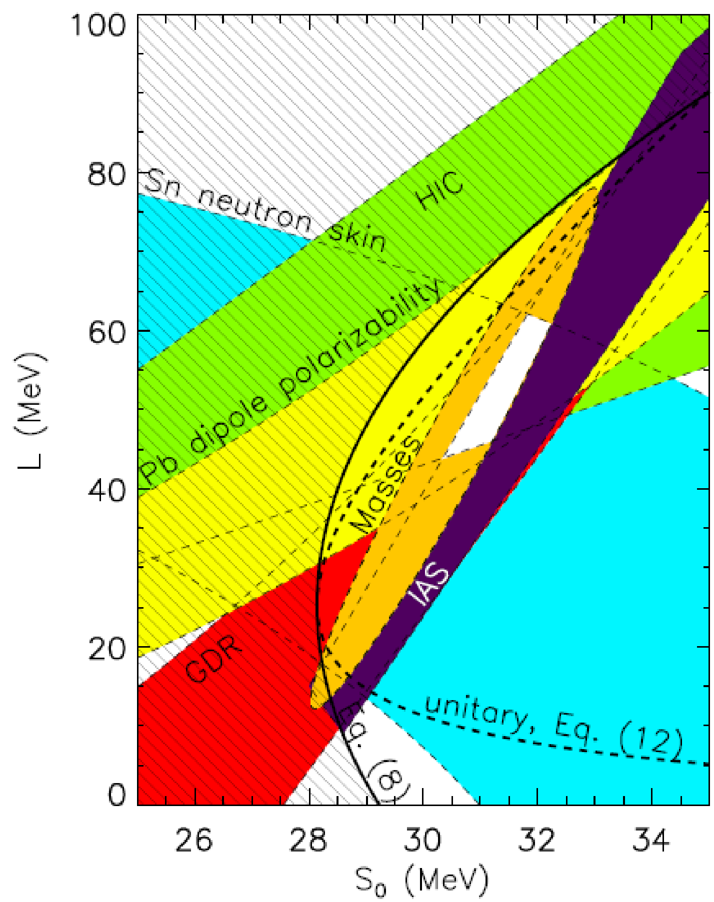
Crossover: Masuda, Hatsuda, Takatsuka ('12)



Tsubakihara, Harada, AO, arXiv:1402.0979

Symmetry Energy Constraints





Many of EOSs in active astrophysical use do not satisfy recent symmetry energy constraint or 2 $M_\odot$ constraint.
→ SFHo, SHFx, DD2

Kolomeitsev, Lattimer, AO, Tews ('16)

What is necessary ?

- **Saturation properties (ρ_0, E_0, K)**
- **Symmetry energy parameters (S_0, L)**
- **Finite nuclear properties (mass, radius)**
- **Hypernuclear separation energies (S_Λ)**
- **Support 2 $M_\odot$ neutron stars**
- **(Neutron star radius at 1.4 $M_\odot$ of 12 ± 1 km)**
- **Hopefully based on microscopic calculations and/or QCD**

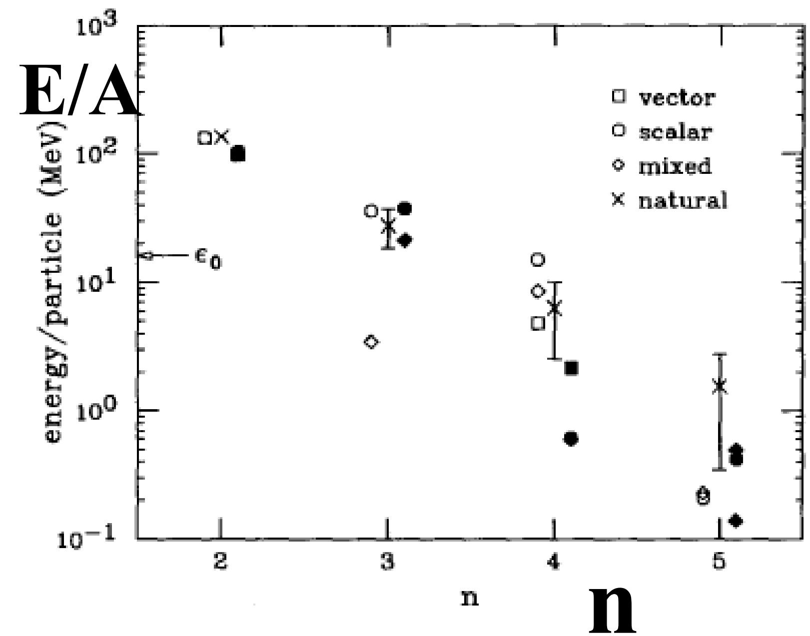
Relativistic mean field model with multi-body couplings

Relativistic Mean Field with Multi-body couplings

- **Phen. Approach: RMF w/ Multi-body coupling**
  - **Naive dimensional analysis (NDA) and naturalness**
    Manohar, Georgi ('84)
    The vertex is called "natural" if C ~ 1 (consistent with pQCD).

$$L_{\rm int} \sim (f_\pi \Lambda)^2 \sum_{l,m,n,p} \frac{C_{lmnp}}{m!\,n!\,p!} \left(\frac{\bar\psi \Gamma \psi}{f_\pi^2 \Lambda}\right)^l \left(\frac{\sigma}{f_\pi}\right)^m \left(\frac{\omega}{f_\pi}\right)^n \left(\frac{R}{f_\pi}\right)^p$$

  - **FST truncation**
    R. J. Furnstahl, B. D. Serot, H. B. Tang, NPA615 ('97)441.
    Truncation the index
    n = B/2 + M + D
    (B: baryon, M: Non NG boson, D: derivatives)
    Natural → V ~ $\rho^n/n!$
    → small for large n



Relativistic Mean Field with Multi-body couplings

- **σωρ model +std. non-linear terms + multi-body couplings**

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\gamma^\mu \partial_\mu - M_N - U_s - \gamma^\mu U_\mu)\psi + \mathcal{L}_{\sigma\omega\rho} \ , \\
\mathcal{L}_{\sigma\omega\rho} =& \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4} R_{\mu\nu} \cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho} \ , \\
U_s =& - g_\sigma \sigma \left[1 - r_{\sigma\sigma}\sigma/f_\pi\right] + g_\sigma \omega^\mu \omega_\mu \left[r_{\omega\omega} - r_{\sigma\omega\omega}\sigma/f_\pi)\right] \ , \\
U_\mu =& g_\omega \omega_\mu \left[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu \omega_\nu/f_\pi^2\right] \\
& + g_\rho \tau \cdot R_\mu \left[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2\right] \ , \\
\mathcal{V}_{\sigma\omega\rho} =& \frac{1}{2} m_\sigma^2 \sigma^2 - a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\sigma^4 + \frac{1}{3}c_{\sigma 3} f_\pi \sigma^3 \\
& - \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu \left[1 - c_{\sigma\omega}\sigma/f_\pi\right] - \frac{1}{4} c_{\omega 4}(\omega^\mu \omega_\mu)^2 \\
& - \frac{1}{2} m_\rho^2 R^\mu \cdot R_\mu \left[1 - c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu \omega_\mu/f_\pi^2\right] - \frac{1}{4} c_{\rho 4}(R^\mu \cdot R_\mu)^2 ,
\end{aligned}
$$

Relativistic Mean Field with Multi-body couplings

- **σωρ model +std. non-linear terms + multi-body couplings**

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu)\psi + \mathcal{L}_{\sigma\omega\rho}\ ,$$

$$\mathcal{L}_{\sigma\omega\rho} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho}\ ,$$

$$U_s = -g_\sigma\sigma\left[1 - r_{\sigma\sigma}\sigma/f_\pi\right] + g_\sigma\omega^\mu\omega_\mu\left[r_{\omega\omega} - r_{\sigma\omega\omega}\sigma/f_\pi)\right]\ ,$$

$$U_\mu = g_\omega\omega_\mu\left[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2\right] + g_\rho\tau\cdot R_\mu\left[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2\right]\ ,$$

$$\mathcal{V}_{\sigma\omega\rho} = \frac{1}{2}m_\sigma^2\sigma^2 - a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\sigma^4 + \frac{1}{3}c_{\sigma 3}f_\pi\sigma^3 - \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\left[1 - c_{\sigma\omega}\sigma/f_\pi\right] - \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2 - \frac{1}{2}m_\rho^2 R^\mu\cdot R_\mu\left[1 - c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2\right] - \frac{1}{4}c_{\rho 4}(R^\mu\cdot R_\mu)^2\ ,$$

Scalar polarizability (A. Thomas)

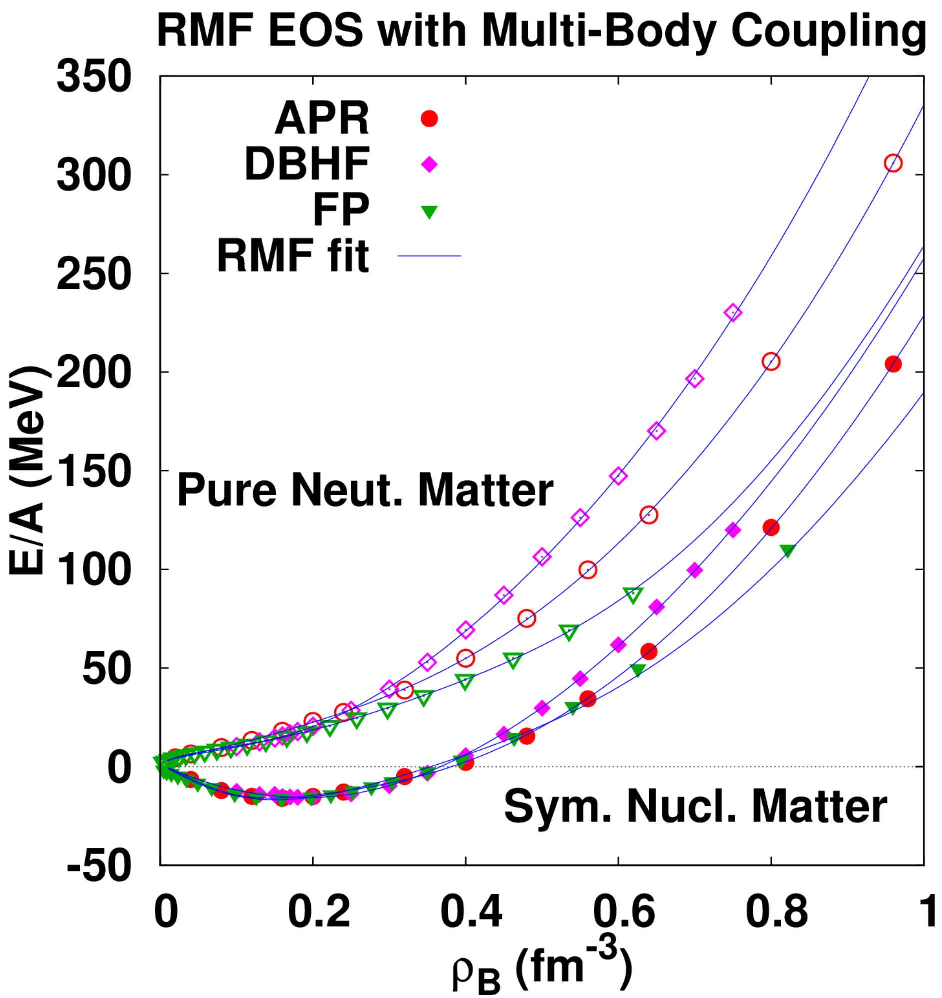
, ω^2 scalar (Typel)

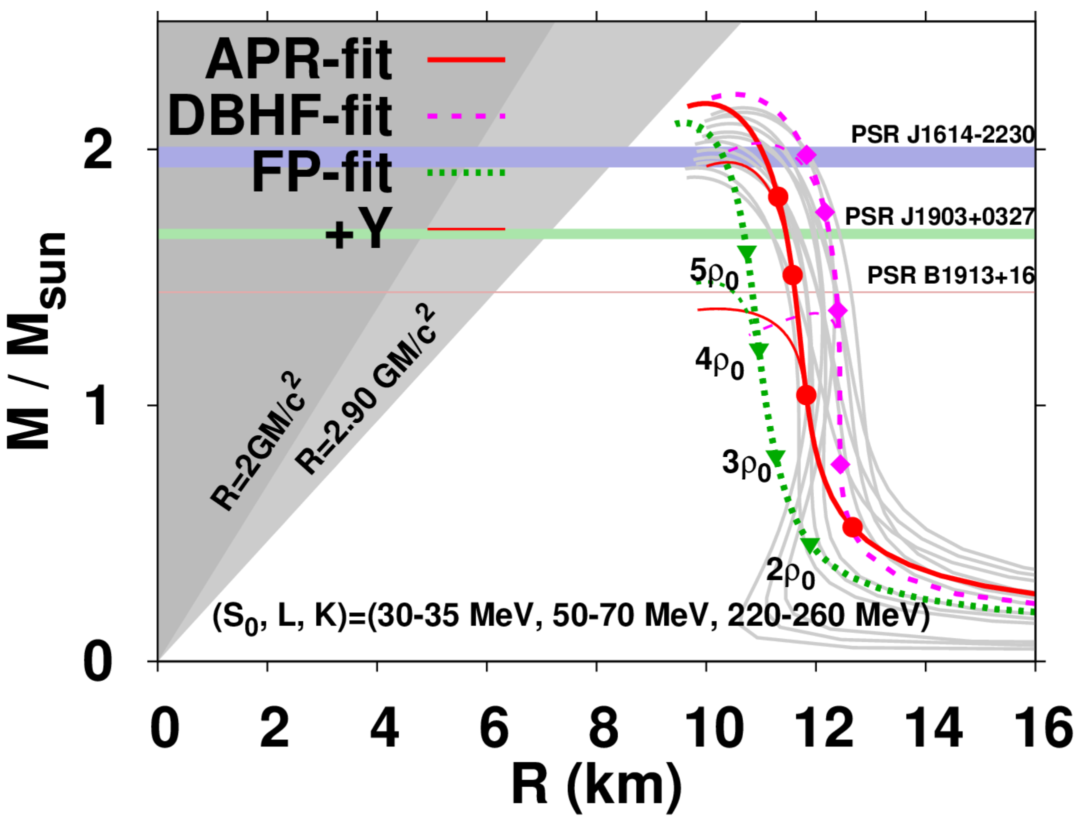
DD coupling (Ring)

ρ^4 term

DD meson mass (e.g. Steiner, Fischer, Hempel)

Fitting "Ab initio" EOS via RMF





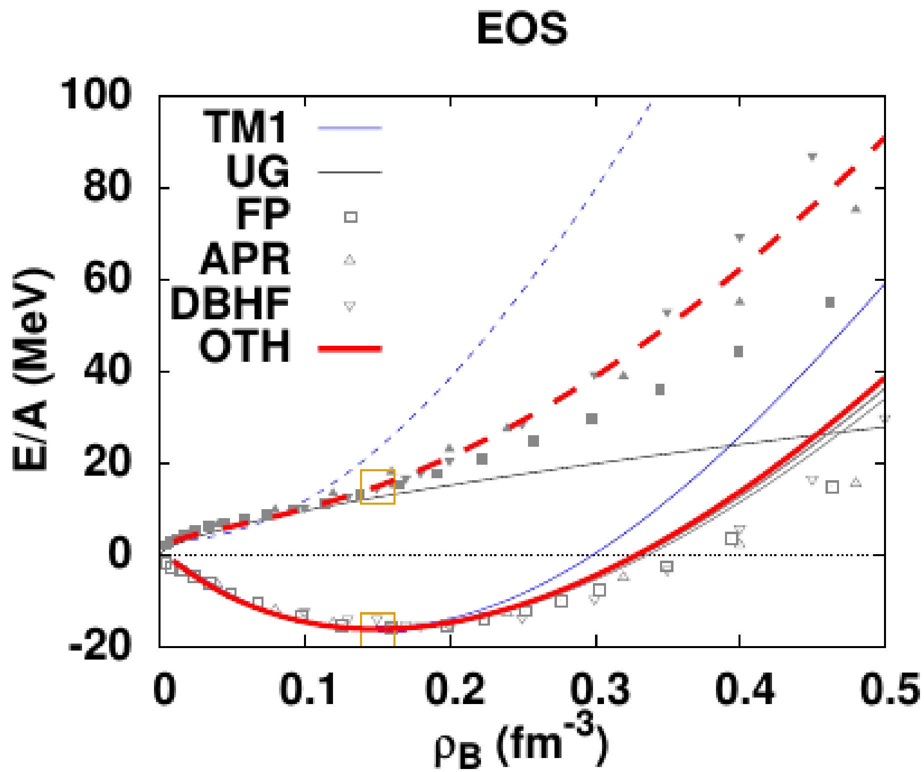
RMF fitting EOS does not necessarily describe finite nuclei….

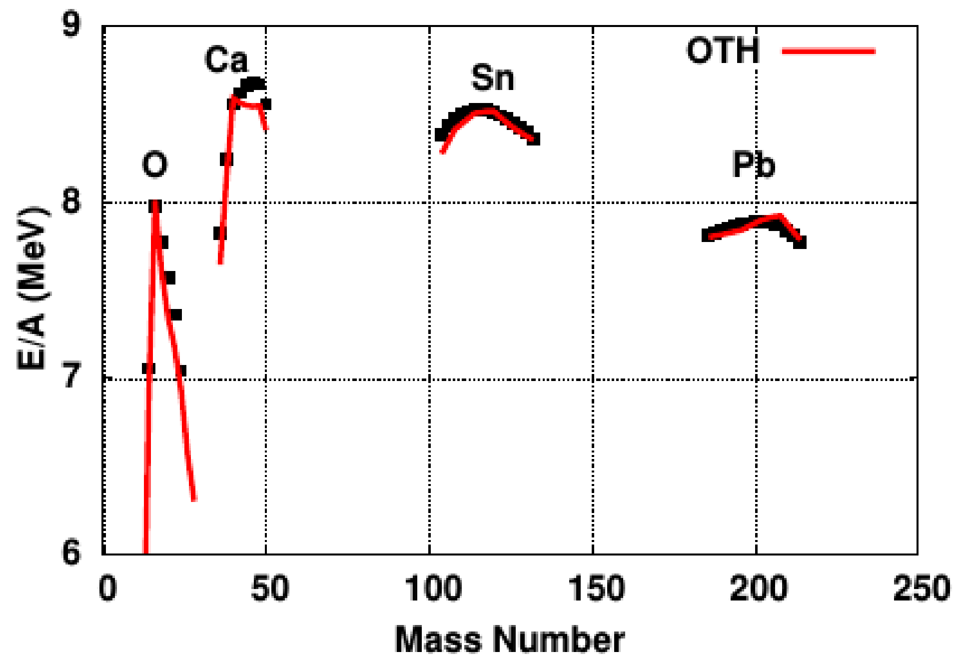
AO, Tsubakihara, Harada ('16, NIC proc.)

Simultaneous Fit to EOS and Finite Nuclei

- **Fitting procedure**

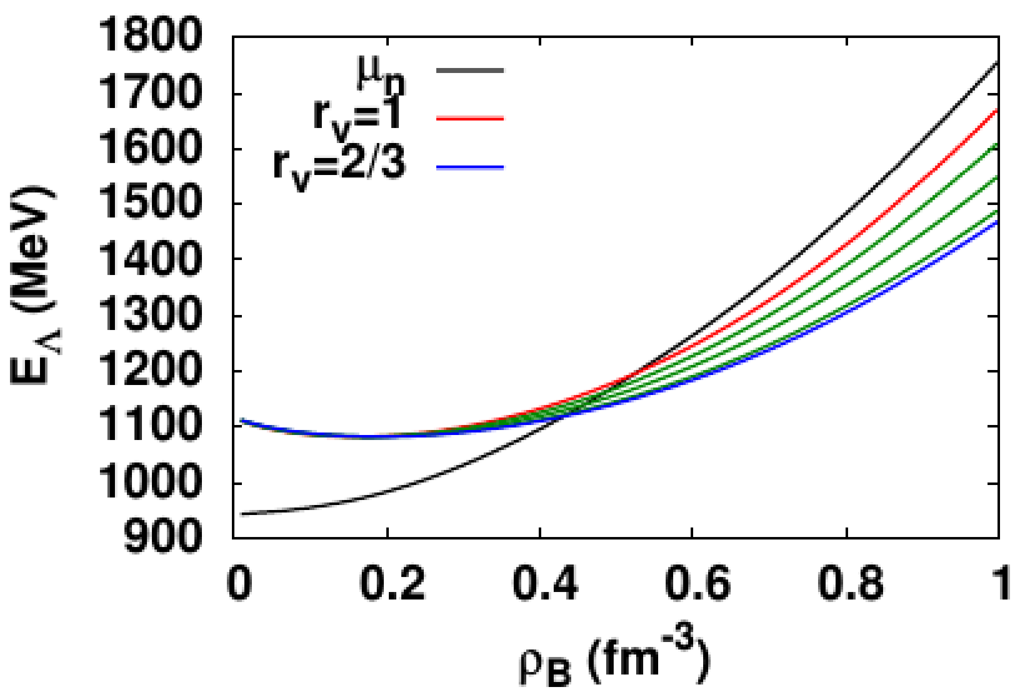
  = **Fit finite nuclear binding energies and charge rms radius under the constraint of given (ρ_0, E_0, K, S_0, L).**

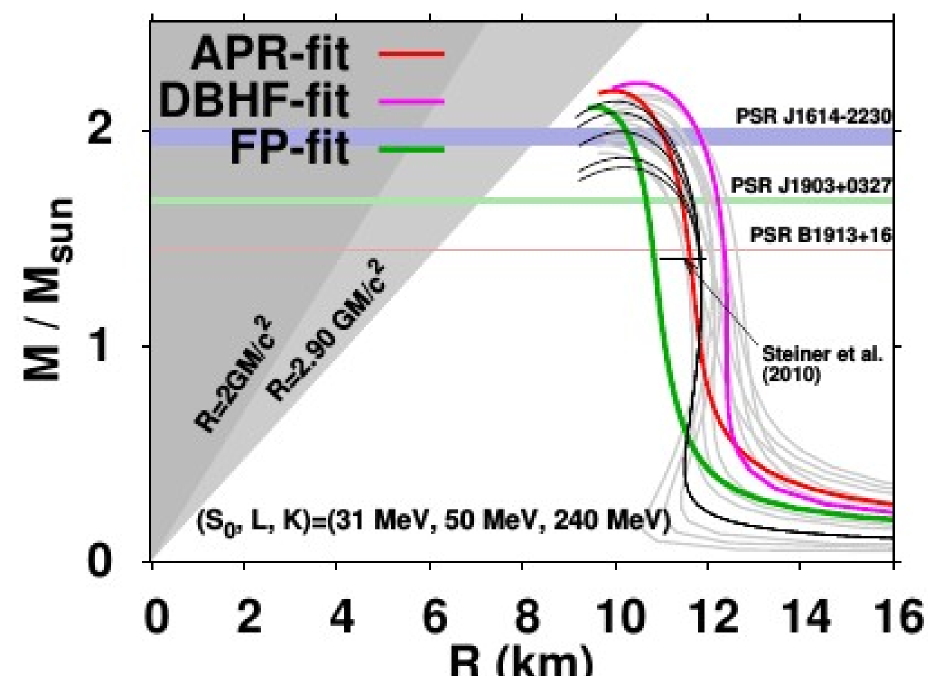




Hypernuclei and Neutron Star MR

- $R_v = g_{\omega\Lambda}/g_{\omega N} = 2/3\text{-}1$ is chosen, and $g_{\sigma\Lambda}/g_{\sigma N}$ is fitted to data. (Other parameters are assumed to be the same.)
  → Λ emerges at $\rho = 0.4\text{-}0.5\ \mathrm{fm}^{-3}$
  2 $M_\odot$ neutron stars may be supported with Rv>0.8
  (Depends on nuclear matter EOS)

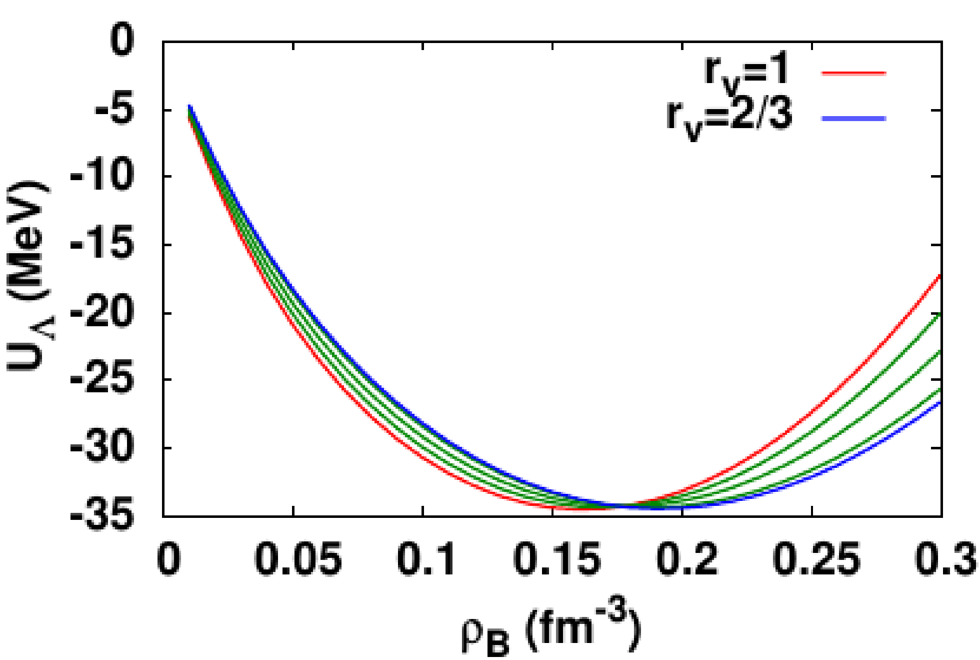


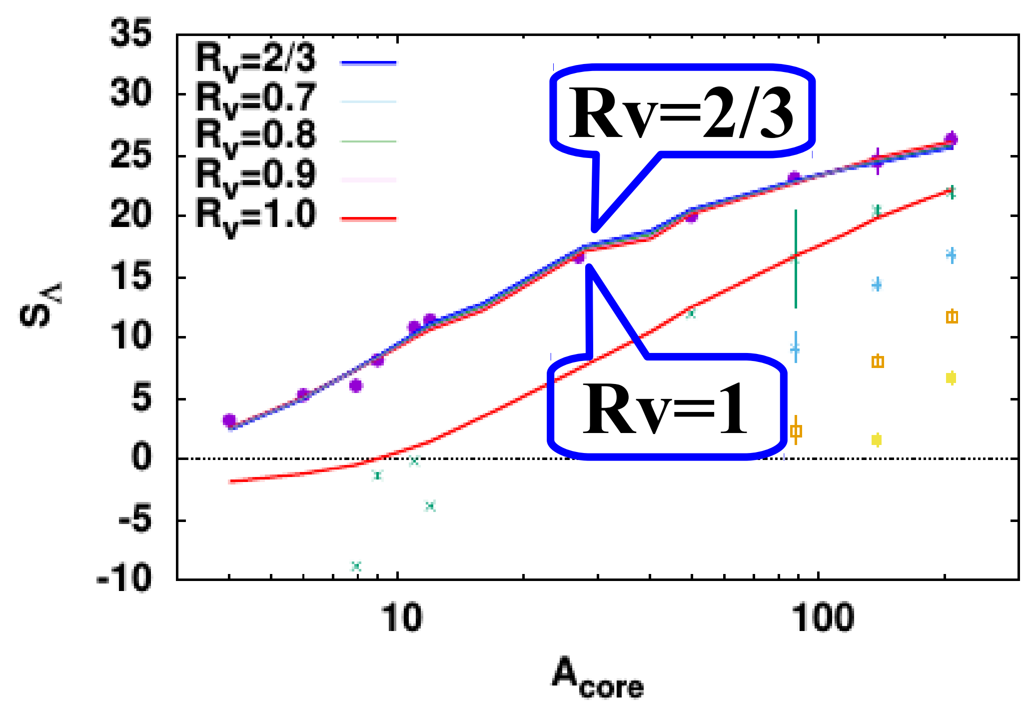


Can we distinguish ?

- **Density dependence of U_Λ**
  - **dU_Λ /dρ turns to be positive at around ρ_0**
    c.f. Talk by Weise, Kohno
  - **Rv=2/3 and 1 leads to the difference of S_Λ of a few 100 keV**

→ sub MeV hypernuclear spectroscopy is necessary



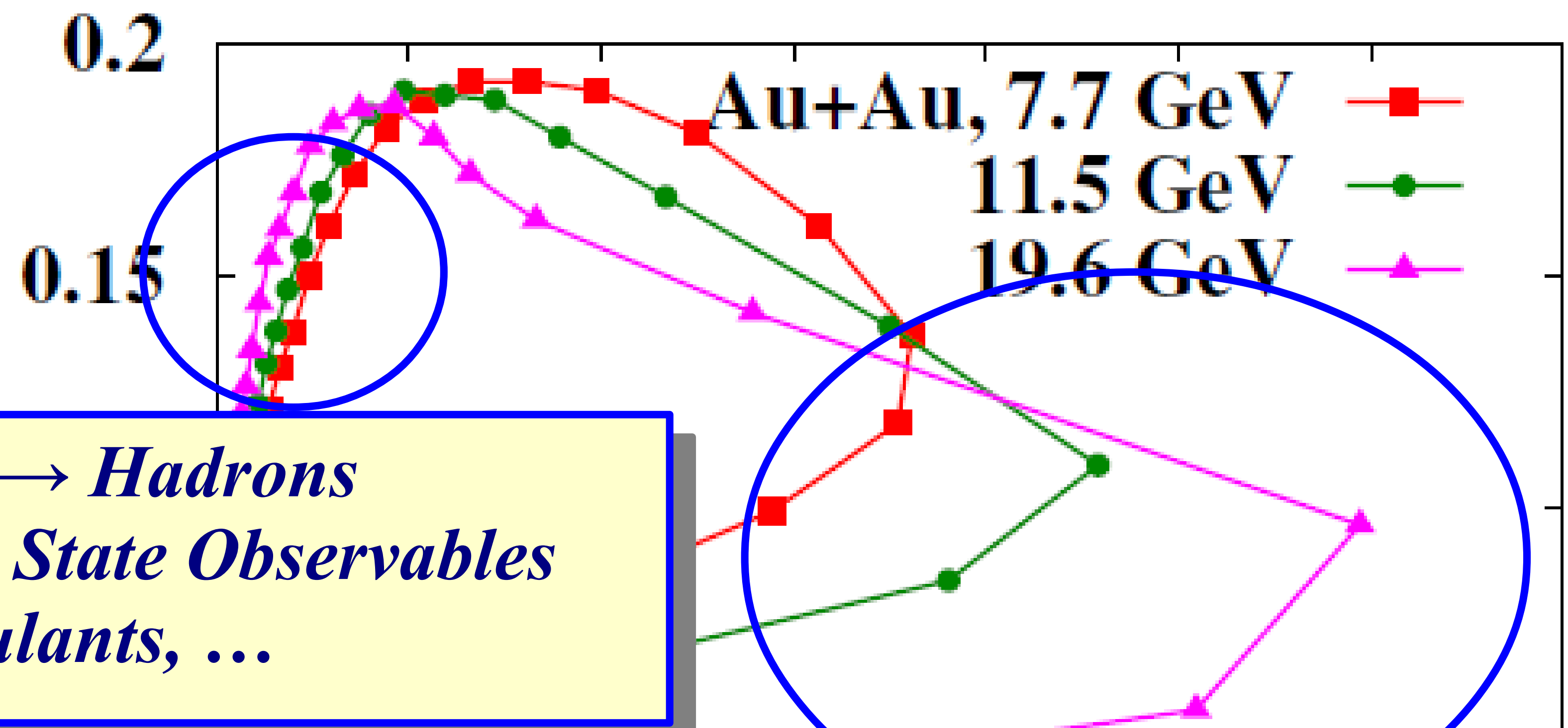


Summary

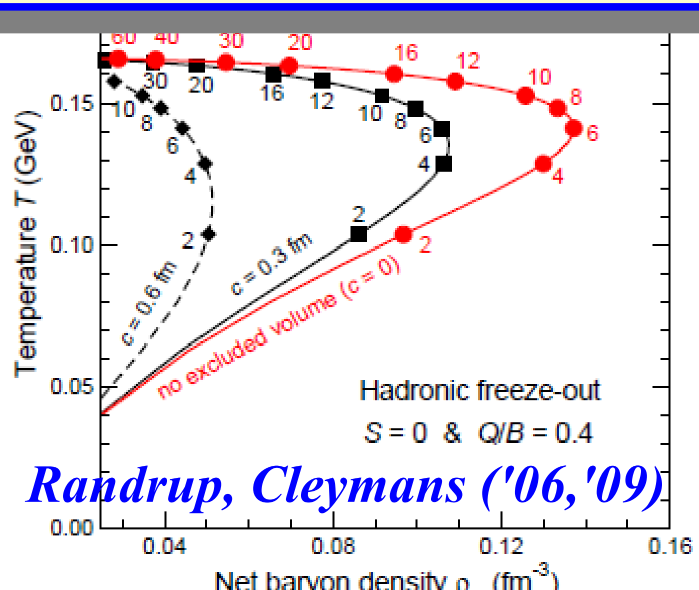
- **In order to answer the hyperon hyperon based on data, we need models which describes**
  normal nuclei, hypernuclei, and nuclear matter
  in a consistent manner.
- **RMF with multi-body coupling may be a handy framework, which is capable of describing**
  saturation point parameters (ρ0, E0, K, S0, L),
  normal nuclei and hypernuclei.
- **Turn over density ($dU_\Lambda/d\rho = 0$) is found to be around ρ_0 , and is found to be sensitive to the maximum mass of neutron stars. Sub MeV hyernuclear spectroscopy may inform us on it.**
- **Central density of NS is around 1-1.2 fm^{-3} (in the present model). HIC and NS suggest the QCD phase diagram with**
  → Stiff hadronic matter at $\rho < 1\ fm^{-3}$
  "Softened state of matter" at $\rho > 1.x\ fm^{-3}$

Thank you !

Two ways to probe QCD phase transition



QGP → Hadrons
Final State Observables
Cumulants, …



Randrup, Cleymans ('06,'09)

Hadrons → QGP
Early Stage Observables
Caution: (Partial) Equilibration is necessary !